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This report summarizes research on the acoustic interaction with the sea floor, carried out during 1981 at Applied Research Laboratories, The University of Texas at Austin. Major topics considered are bottom structures having near-surface layering, and propagation over slopes. Other topics include bottom interaction in shallow water, the effects of bottom roughness, and the bottom interaction phase shift.

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I. INTRODUCTION

For a wide variety of source-receiver geometries, frequencies, sound speed profiles, and water depths, sound propagation in the oceans can be heavily influenced by the ocean subbottom. It is now recognized that this acoustic bottom interaction can have an important effect on sound propagation over the ranges, frequencies, and geometries of concern to ASW applications. Applications which are affected by bottom interaction include system performance prediction, system design, interpretation of acoustical data, geoacoustic profile development, propagation modeling, and the design of experiments to gather acoustic data. Thus, a thorough description of bottom interaction effects is needed.

Traditionally, a single quantity, bottom loss, has been used to characterize the effects of bottom interaction. This quantity can be sufficient for many applications, such as ray trace calculations used to estimate propagation loss in some system performance models, which rely on a simple description of the acoustic field.

However, a more detailed characterization of the sea floor is required to understand and use more complex phenomena, such as phase interference between multipaths, Doppler line broadening, multipath (or mode) conversion due to range changing bathymetry, propagation in complex shallow water environments, and questions related to array performance. A simple regional characterization in terms of bottom loss estimated in octave bands is not enough, especially for cw applications. Fairly comprehensive descriptions of the ocean subbottom may be required, including detailed sound speed and absorption profiles, the location of reflecting interfaces, shear wave parameters, surface and basement scattering parameters, bottom slopes, and lateral changes in subbottom geoacoustic parameters.

With NAVELEX Code 612 (formerly 320) sponsorship (through a program administered by NORDA Code 530), ARL:UT has been conducting a study of the influence of the ocean bottom on sound propagation characteristics. In view of the various levels of description of the ocean bottom required by the intended applications, this study has encompassed four primary research areas: (1) the influence of subbottom parameters on bottom loss, (2) the role of the bottom in range changing environments, particularly problems involving slopes, range variable subbottom structures, and bottom roughness, (3) the effect of the subbottom on the coherence of the sound field, and (4) bottom interaction effects such as those involved in array studies, cw line structure, and experimental acoustic data interpretation.

From the outset the primary goals of the ARL:UT bottom interaction research program have been fourfold: (1) to determine and provide guidance on the level of detail of subbottom parameters required for acoustic applications (sensitivity studies), (2) to determine which aspects of mode (or multipath) conversion caused by slope coupling, lateral variability, and roughness are predictable and exploitable, (3) to develop computational tools appropriate to the study of a wide range of complex bottom interaction problems, and (4) to interact with experimental measurement programs via exercise planning and data analysis and interpretation.

During the past year (1981) there were four areas of investigation: (1) loss processes in horizontally stratified deep sea sediments, (2) bottom interaction in range changing environments, (3) coherence of bottom interacting energy, and (4) bottom interaction in shallow water. The first and last were new starts in 1981; the middle two were continuations of 1980 work. Research in the first, second, and fourth areas is expected to continue into 1982.

This report contains a summary of the progress made in each of the research areas. This work will be documented in detail through journal articles and other reports as the projects reach maturity. Appendix A

is a listing of documentation appearing in 1981. Appendix B contains documentation for the complete project to date. Appendixes C and D contain journal articles based on this year's work that have been submitted for publication but have not yet appeared in print.

II. LOSS PROCESSES IN HORIZONTALLY STRATIFIED DEEP SEA SEDIMENTS

A continuing aspect of bottom interaction studies at ARL:UT is the use of bottom reflection loss as a "measure" of bottom interaction. In this work computational models of bottom reflection loss are used as vehicles for determining the major loss processes and the importance of subbottom parameters and their uncertainties. Recent studies have explored the acoustical importance of sea floor parameters such as density, sound speed, shear speed, absorption, and their gradients.

A. Review of Previous Work

The study of the sensitivity of bottom reflection loss to subbottom parameter variations began in 1976. Initially the work concentrated on the properties of a fluid sediment, and used a computational model[1] developed at ARL:UT. The importance of sea floor parameters such as density gradient,[2] sound speed,[3] absorption gradients,[4] and substrate rigidity[5,6] was established.

In 1978, the direction of these studies turned toward the inclusion of shear wave propagation within the sediment. A new computational model of bottom reflection loss from a single solid sediment layer was developed[7] to gauge the importance of sediment shear wave excitation. Initial studies[8] using this model showed that sediment shear wave excitation is not important for areas having thick sediment cover, but could be dominant in areas of thin cover. For thin sediment cover, the impact of sediment shear waves is greatest at low frequencies where propagation of shear waves within the sediment causes resonance to occur. At high frequencies the resonance structure is absent, but the energy lost to sediment shear waves is still substantial. A ray path analysis[9] of processes in a thin sediment layer over a substrate

established compressional wave conversion at the substrate interface as the physical mechanism generating shear waves in the sediment. This analysis resulted in a detailed understanding of the physical processes by which sediment shear waves influence bottom reflection loss. Further sensitivity studies[10] have identified important subbottom parameters affecting bottom reflection loss from thin sediment layers.

The understanding of bottom reflection loss resulting from these studies of a single deep sea sediment layer has been synthesized in a coherent structure[11] for use in modeling applications. The major loss processes were identified, and a small set of linked geoacoustic profiles and computational models keyed to these processes was developed. The loss processes included were reflection, refraction, absorption, and shear wave excitation. Scattering from rough interfaces may be an additional major loss process for a thin layer, but was not well enough understood to be included in the synthesis.

The goal of this synthesis was to develop a structure that can be used along with relatively modest information to determine bottom loss and phase shift using the most efficient computational approach. Given sediment thickness, type, and physiographic province, it is relatively straightforward to predict fairly accurate compressional wave properties.[12] These can be used, along with frequency and grazing angle, to decide whether the sediment is thick or thin. If it is thin, very crude estimates of shear wave attenuation can be used to decide whether the frequency is high or low. The type of geoacoustic profile and requirements for the computational model are then chosen.

The level of detail required to adequately model sediment shear wave effects is a matter of practical interest. If the sediment in an area is thick for the intended applications, it is not necessary to carry out experiments designed to measure shear wave parameters. If the sediment is thin but the application is high frequency, it is not necessary to develop modeling techniques to handle the short wavelength, heavily attenuated sediment shear waves; only their excitation needs to

be modeled. Knowing these requirements before the fact can save substantial measurement and computational effort.

Four generic geoacoustic profiles were developed for use in modeling a single sediment layer overlying a substrate. The first profile includes only the fluid parameters of the water-sediment interface. The second profile adds the depth dependent compressional wave velocity and absorption as parameters. The third profile adds the substrate parameters and the sediment shear velocity at the substrate. The fourth, and most detailed, profile adds the depth dependent shear velocity and attenuation.

These four geoacoustic profiles are associated with a set of dominant physical processes and hence computational requirements. For the first profile, the dominant process is reflection from the water-sediment interface. It is appropriate for use at high frequencies for which any energy entering the sediment is totally absorbed. The second profile adds compressional wave refraction and absorption within the sediment. It is appropriate for cases in which the compressional wave does not interact with the substrate, i.e., low grazing angles. The third profile adds the effects due to interaction with the substrate and the energy lost to sediment shear waves at the substrate. It can be used for frequencies high enough for the sediment shear wave to be totally absorbed in the sediment. The fourth profile adds effects due to sediment shear wave propagation through the sediment layer and the reconversion of energy back to compressional waves.[11]

B. Major Results of Work in 1981

Work begun in 1981 represents a change in the level of complexity of subbottom structure being examined. At this time, most of the processes occurring in a single sediment layer over a substrate with smooth interfaces are quantitatively understood. This year we are beginning to examine more complex structures. The major emphasis is on determining the major loss processes in layered sediments and on characterizing the effects of scattering from rough interfaces.

Efforts in 1981 were stimulated largely by problems associated with the Bottom Loss Upgrade Project (BLUG), sponsored by the Tactical ASW Environmental Acoustic Support (TAEAS) and Surveillance Environmental Acoustic Support (SEAS) programs and carried out in part at ARL:UT. Two specific bottom interaction problems were identified by BLUG. The first is the existence of anomalously low bottom loss areas in nominally thick sediment areas in the Atlantic. NADC bottom loss data from these areas can have octave averaged bottom loss at 1600 Hz as low as 5 dB at high grazing angles. For these thick sediment areas one would expect that any high frequency energy entering the sediment at high grazing angles would be completely absorbed in the sediment and would not return to the water column. Bottom loss would then be given by the reflection coefficient of the water-sediment interface. For the sediment types typical of these deep ocean areas, the expected bottom loss would be about 15 dB. To cope with this large discrepancy compared to the measured 5 dB loss, the BLUG geoacoustic profiles for these areas contain a nonphysical, thin, high density surface layer to enhance the reflected energy. Since the actual mechanism leading to the anomalous reflectivity is not known, there is concern about the usefulness of these BLUG profiles and the correct means for extrapolating them geographically. During FY 81 ARL:UT identified and investigated two potential mechanisms: hydrate formation in marine sediments, and small scale, near-surface layering.

The second BLUG problem area is associated with defining the geoacoustic parameter set for the areas of the Pacific having thin sediment cover. The current BLUG parameter set does not include sediment shear wave parameters, nor does it treat scattering from the rough basaltic basement. The basement interaction is included through an angle and frequency independent reflectivity parameter.

In 1981, our major effort was aimed toward understanding the effects of hydrate layers and near-surface layering on bottom reflection loss. We also began parameter studies of scattering from the basement, particularly aimed at establishing the role of sediment shear wave

excitation. A small effort was made to further understand the generic geoacoustic profiles for a single sediment layer.

1. The Effect of Near-Surface Layering on the Reflectivity of the Ocean Bottom

One of the possible mechanisms for producing the anomalously large high frequency, high angle reflectivity in nominally thick sediment areas is the cumulative effect of scattering from a number of near-surface layers. To investigate this possibility, the effect of a series of thin near-surface layers in an otherwise thick sediment on bottom reflection loss was performed. Both artificial (equidistant) and naturally occurring layering structures were examined over a frequency range from 25 to 1600 Hz. For comparison with data, both cw and 1/3 octave averaged bottom reflection losses were studied. The results of this study are reported in detail in Appendix C. A brief summary of the results is given here.

Near-surface layering in marine sediments can have an important effect on bottom reflection loss (BRL). Computations of BRL for sediment structures 500 m thick with realistic near-surface layering show that, relative to an unlayered structure, additional reflections from the layering can reduce 1/3 octave averaged BRL (BRLA) more than 10 dB at 1600 Hz for grazing angles above 20°. This reduction is smaller at lower frequencies, but is still noticeable at 200 Hz; at 50 Hz the layering has almost no effect. The lowered BRLA near 1600 Hz results in a frequency inversion in which BRLA tends to decrease, rather than increase, with frequency from 500 to 1600 Hz.

An important feature of this dramatic decrease in BRLA at 1600 Hz is its relative independence from the details of the layered structure. If special structures were required to achieve the reduction, the variability in naturally occurring layering would restrict the effect to a few special geographic areas. This relative independence from the exact structure suggests that such reductions and

associated frequency inversions may actually occur in a wide variety of locations, and that statistical parameters such as mean layer spacing, thickness, number of layers, etc., may be controlling factors.

The exact nature of the layered structure has several important effects. Above 200 Hz, the layering structure is critical in predicting the dependence of BRL, and especially cw bottom reflection phase shifts, on grazing angle. At lower frequencies, where the long wavelength acoustic field averages over the layering, BRL and phase shift nearly equal those computed for an unlayered structure. The details of the layered structure also have an important effect on BRLA at about 800 Hz, but this sensitivity may decrease for larger averaging bands.

Frequency averaging smooths the dependence of BRL on grazing angle. The 1/3 octave averaging used in this study has a considerable effect, and further smoothing may well occur for larger averaging bands such as a full octave. This smoothing effect suggests that caution be used in applying measured band averaged BRL in the analysis of cw propagation.

The physical mechanism responsible for the reduction in near-normal incidence BRL is a collective effect of the layered structure. Studies of BRL using an artificial layered structure made up of identical, equally spaced layers show that the constructive interference of reflections from each layer produces the decrease in BRL. Detuning the structure by modifying the layer spacing slightly reduces the magnitude of the decrease in BRL, but does not change the frequency interval over which the decrease occurs. Thus, equally spaced, identical layers are not required for the collective resonance effect to be an important mechanism.

These studies treated the sediment as a fluid. Further work is needed to establish the role of shear wave excitation. The possibility that statistical parameters control the low loss at high frequencies suggested by this work also needs to be investigated.

2. Occurrence and Acoustical Significance of Natural Gas Hydrates in Marine Sediments

The occurrence of some of the anomalously low bottom loss areas in regions where natural gas hydrates are suspected in marine sediments led to a study of reflection from hydrate layers. This work is speculative since no estimates of the shear wave parameters of hydrates are available at this time. The results of this work are reported in detail in Appendix D. A brief summary is given here.

The crystal-like gas hydrate molecules that are found in marine sediments can significantly alter the geoacoustic properties of these sediments. Laboratory evidence indicates that significant increases in compressional sound velocity (i.e., from 1.8 to 2.7 km/sec) occur as well as changes in the thermal and electrical properties. In situ results confirm the effects observed in laboratory experiments. Whether similar changes occur in shear velocities, and both compressional and shear attenuations, is a question that remains to be answered.

There is evidence for the widespread occurrence of hydrates. The temperature and pressure conditions necessary for the formation of hydrates are found globally. Considerable research is needed to determine the actual extent of gas hydrates as well as the possible structures hydrates can assume. Bottom simulating reflectors and seismic bright spots are believed to be caused by hydrate zones; dramatic acoustic changes would also be caused by both continuous hydrates zones and diffuse patches of hydrates, which are not detectable under normal seismic profiling conditions.

Preliminary results obtained through calculations of bottom reflection loss show that hydrates may have a profound impact on underwater acoustics. Using estimates of potential shear wave parameters, it was established that reductions in bottom loss at high

frequencies and large grazing angles similar to that observed in data can occur. The actual values of the shear wave parameters in hydrates, which are not known at this time, will determine whether reflection from hydrate zones is actually responsible for the observed low BL.

3. Scattering from a Rough Substrate

Two major phenomena are to be included in studying scattering from a rough substrate. The first is the effect of shear wave excitation; the sediment must be treated as a solid since the interaction with the basement generates shear waves in the sediment. The second phenomenon is the effect of correlation. If energy lost out of the specular direction is significant, then effects due to the mean slope as well as the mean height need to be properly treated.

During 1981, the first of these phenomena was studied theoretically to determine the effect of scattering from a single sediment layer over a rough substrate when correlation effects are negligible. Initial parameter studies indicate that scattering for 1 m rms height the scattering of shear waves is so strong that energy given to them is effectively removed from the system. This is physically equivalent to a very large shear wave attenuation.

Further studies of scattering from the substrate and the effects of the correlations are expected to continue in 1982. Detailed documentation of the results of these studies will be prepared when they are completed.

4. Generic Geoacoustic Profiles for Thin Sediment Areas

Work on this topic is nearly completed. Additional parameter studies were conducted and techniques developed and tested for producing an automated bottom reflection loss module for use in other aspects of bottom interaction research. The primary characteristic of this module is the ability to choose the most efficient computational technique for

the set of input parameters. Refinement of this approach and detailed documentation are expected to be completed in 1982.

III. BOTTOM INTERACTION EFFECTS IN A RANGE CHANGING ENVIRONMENT

The work encompassing acoustic propagation in a range variable environment is summarized in this section. The effect of both sloping bottom and lateral subbottom variability is discussed.

The work on sloping bottoms has the goal of determining which factors significantly influence acoustic propagation in such areas. One such factor is the particular geometry, e.g., continental slope, sea mount, etc. A second factor influencing propagation is the bottom composition. After determining the relative importance of the geometry and the geoacoustic profile of the bottom, a second goal is to ascertain the level of detail in geometry or geoacoustic profile necessary to characterize propagation.

In the study of acoustic propagation in the presence of lateral variability, the extent to which naturally occurring inhomogeneity is significant and the method and detail of including such effects in the propagation model are important issues.

A. Review of Previous Work

1. Sloping Bottom

By the beginning of 1980, the adiabatic normal mode model was established as a reliable tool for studying propagation in range variable environments. The 1980 work on sloping bottoms then proceeded with a study of the sensitivity of upslope and downslope propagation to subbottom attenuation. These topics were discussed in Ref. 13, where the mechanisms governing propagation in sloping bottom environments were established and used to demonstrate the sensitivity of propagation over

slopes to the sediment attenuation values in the shallow water portion of sloping bottoms.

2. Lateral Variability

The effects on shallow water propagation of range variable sediment attenuation were studied. Range variation of the depth gradient of attenuation was found not to be particularly important. A comparison of range averaged and province type descriptions was made for an absorbing patch. These results are discussed in Ref. 14.

B. Results of 1981 Research

1. Sloping Bottom

The 1980 work on propagation over sloping bottoms showed that adiabatic normal mode analysis was a powerful method for a general understanding and characterization of the acoustic field produced by sources at long range. The ADIAB model could be used to determine the extent to which the specific features of the environment cause one or another propagation mechanism to dominate. In particular, one portion of the 1981 research[14] examines the extent to which the sediment type determines the sensitivity to attenuation observed in the earlier work.

The results of the 1981 work indicate that sediment type is indeed an important factor in the sensitivity of propagation to attenuation. The acoustically softer sediments, such as clay or silt, that were used in the 1980 modeling showed much greater sensitivity to attenuation than was found for harder sediments such as sand. This decreased sensitivity of harder sediments is especially noticeable at the higher attenuation values characteristic of sands.

Another aspect of the importance of sediment type is that propagation is sensitive to sediment attenuation gradients in the shallow portions of slopes with softer sediments.

The partitioning of power between bottom interacting and waterborne modes was also considered in the slope propagation studies. These results showed that almost all of the upslope propagating power is in bottom interacting modes before the midpoint of the slope where the sound channel meets the bottom. The power partition is of much more interest for upslope propagation than for downslope propagation because the power carried by a particular mode is dependent upon source depth only.

Finally, a comparison between the models used for the 1980 and 1981 studies indicates that slope propagation sensitivity to the attenuation values of softer sediments may depend strongly on the water-sediment sound speed ratio.

2. Lateral Variability

One of the environmental complications of the continental slope regions of the world's oceans is the variability of bottom composition along the slope. The sloping bottom studies indicate that the bottom composition of the shallow portions of the slope is important. However, these studies did not consider variation in sediment type as the slope is traversed. Sloping bottom and lateral variability must be considered together in constructing geoacoustic models for continental margins. The 1981 study of this problem, although not comprehensive, indicates that the sound field levels at the shallow end of the slope for upslope propagation are insensitive to the deep water bottom type. Of course, the deep water bottom type will still be important in determining the sound field levels on the deeper regions of the slope.

C. Future Directions

The prediction of ambient noise fields produced by shipping has been a topic of controversy in the recent acoustical literature. The controversy could be resolved by examining bottom interaction effects

due to bathymetry changes, using adiabatic normal mode analysis. For example, the understanding of renormalization effects should reduce the number of variables which enter the ray theory explanation of slope enhancement effects. Indeed, the low frequencies at which shipping noise dominates wind generated noise indicate that a normal mode analysis would be appropriate at this time.

Another problem also applicable to ambient noise is the problem of propagation oblique to bathymetry gradients. The questions here relate both to slope mounted arrays and to propagation from sources in narrow vertical wave guides such as straits.

Finally, the questions of the frequency and depth dependence of sediment attenuation appear to be as yet unresolved.[15] A study of the effects of propagation over laterally varying sediments could help resolve this question. Depending upon the type of frequency or depth dependence actually possessed by sediments, the sensitivity to range gradients, etc., may be more than observed in Ref. 14.

IV. BOTTOM INTERACTION EFFECTS ON COHERENCE

For situations in which the phase information of the acoustic field is not important, the effect of the ocean bottom is now reasonably well understood in a variety of circumstances. Major loss processes have been identified and, at least for single layer sediments with lateral homogeneity, bottom reflection loss curves generated from relatively simple geoacoustic models adequately describe the field amplitude.

In contrast, a sophisticated description of the phase information in the acoustic field does not yet exist. The mechanisms by which the interaction with the ocean bottom produces phase shifts, the magnitude of the shifts, and the detail in the geoacoustic profile adequate to predict the phase shifts need to be investigated.

During 1981 progress was made in determining the level of detail required in the geoacoustic profile to accurately predict the phase of the plane wave reflection coefficient of the ocean floor. Studies of the sensitivity of the phase shift to subbottom parameter variations show that the level of detail is not much more than that required to predict bottom loss.

Table I gives the geoacoustic profile studied, while Table II summarizes the results of these studies.

Each parameter in the geoacoustic profile was varied about the value given in Table I. The categories of high (H), medium (M), and low (L) sensitivity were assigned to the parameters based on the change produced by a ±10% variation. For bottom reflection loss, a high sensitivity parameter produced more than a 15% change in the reflection coefficient for a 10% change in the parameter. A medium sensitivity parameter produced a change of between 5% and 10%, the same size as the

TABLE I

LIST OF GEOACOUSTIC PARAMETERS USED TO STUDY THE PHASE OF THE REFLECTION COEFFICIENT: 40 m OF CLAY OVER BASALT

LOCATION	PARAMETER	SYMBOL	VALUE
Water	sound speed	C_{p1}	1547 m/sec
	density	ρ_1	1.052 g/cm^3
Sediment	compressional velocity	C_{p2}	1516 m/sec
Surface	compressional velocity gradient	C'_{p2}	1/sec
	compressional attenuation	k_{p2}	0.03 dB/m-kHz
	compressional attenuation gradient	k'_{p2}	2.5×10^{-4} dB/m^2-kHz
	density	ρ_2	1.37 g/cm^3
	density gradient	ρ'_2	1.25×10^{-3} g/cm^3-m
	shear velocity	C_{s2}	116 m/sec
	shear velocity gradient	C'_{s2}	4.3/sec
	shear attenuation	k_{s2}	15 dB/m-kHz
	shear attenuation gradient	k'_{s2}	-0.15 dB/m^2 m-kHz
Substrate	compressional velocity	C_{p3}	5200 m/sec
	compressional attenuation	k_{p3}	0.02 dB/m-kHz
	density	ρ_3	2.66 g/cm^3
	shear velocity	C_{s3}	2600 m/sec
	shear attenuation	k_{s3}	0.07 dB/m-kHz

TABLE II

SENSITIVITY OF THE MAGNITUDE R AND PHASE ϕ OF THE PLANE WAVE REFLECTION COEFFICIENT TO VARIATIONS IN SUBBOTTOM PARAMETERS: INITIAL PARAMETERS GIVEN IN TABLE I. GRAZING ANGLES CONSIDERED ARE BELOW 40° AND THE FREQUENCY RANGE IS 18-19 Hz.

Parameters	Change in parameter (%)	Change in R (%)	Change in ϕ (deg)	Sensitivity for R	Sensitivity for ϕ
C_{p1}	±1	27	7	H	H
ρ_1	2	2.9	5	H	H
C_{p2}	1	70	5	H	H
C'_{p2}	10	3.9	1.5	L	L
k_{p2}	10	0.03	1	L	L
k'_{p2}	10	0.02	0.1	L	L
ρ_2	10	5.2	9	M	M
ρ'_2	10	0.20	1	L	L
C_{s2}	10	33	20	H	H
C'_{s2}	10	23	20	H	H
k_{s2}	10	7.5	3	M	M
k'_{s2}	10	2.9	1	L	L
c_{p3}	10	12	3	M	M
k_{p3}	10	0.01	0.1	L	L
ρ_3	10	10	6	M	M
C_{s3}	10	29	20	H	H
k_{s3}	10	0.07	0.1	L	L

parameter variation. A low sensitivity parameter produced a change of less than 5%. For the phase shift, a high sensitivity parameter produces a change in ϕ, the phase of the reflection coefficient, of more than 9° (a change of more than 0.15 in $\sin\phi$). A medium sensitivity parameter produced a change between 3° and 9°. A low sensitivity parameter produced a change of less than 3°.

V. BOTTOM INTERACTION IN SHALLOW WATER

The nature of bottom interaction in shallow water differs from that in deep water in two principal ways. First, the reduced water depth to wavelength ratio, usually combined in the absence of a significant sound channel, implies that propagation is frequently bottom limited, especially at low frequencies. Second, the geophysical processes responsible for sedimentation in shallow water often produce sand sediments, which are unknown in the deep basins. These same processes are of a smaller spatial scale than those responsible for the structure of deep water sediments, and therefore a higher degree of lateral variability in bottom composition results.

These two features make the shallow water bottom interaction problem more severe, the first by producing bottom limited conditions, and the second by introducing more lateral variability, as well as increasing the importance of bottom scattering. A slight easing of the situation is produced by the emphasis in shallow water on shorter ranges than in deep water. For example, the need for extreme precision in low grazing angle bottom loss predictions may not be present in shallow water.

The primary emphasis of low frequency bottom interaction research has been on problems related to propagation in deep water. Rapid advances have been made in characterizing the effects of the bottom on acoustic propagation, isolating dominant subbottom parameters, identifying major physical processes, and determining the level of detail of subbottom description.

The presence of sand sediments in shallow water areas raises the possibility that additional bottom loss processes, not important in the

clay and silt sediments typical of deep water areas, may be major factors in the bottom interaction. In particular, the gradient driven coupling between shear and compressional waves may be significant. For typical deep ocean sediments, this coupling is negligible for frequencies above about 3 Hz.[16] However, the large near-surface gradients in sand sediments[17] may make it a significant mechanism for exciting shear waves within the sediment at significantly higher frequencies. The relatively high attenuation of shear waves[18] in the sediment makes this a potentially important loss process.

Work performed by ARL:UT during 1981 was aimed at establishing the role of the gradient driven coupling in sand sediments. Theoretical work completed in 1981 showed that the coupling occurs over a fairly narrow depth interval near the sediment surface and that the coupling may be important for frequencies up to about 60 Hz.[19] Parameter studies are needed to establish the magnitude of the coupling and its importance as a loss process; these are planned for next year.

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APPENDIX A

1981 CUMULATIVE DOCUMENTATION

PRECEDING PAGE BL

Reports

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APPENDIX C

THE EFFECT OF NEAR-SURFACE LAYERING ON THE REFLECTIVITY OF THE OCEAN BOTTOM

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The effect of near-surface layering on the reflectivity of the ocean bottom

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The effect of near-surface layering in marine sediments on the plane wave reflection coefficient, R, of the ocean bottom is examined using a numerical model. A comparison of bottom reflection loss, BRL = $-20 \log_{10} (|R|)$, from a 500 m thick sediment with and without realistic near-surface layering shows that additional reflections from the layering can reduce 1/3 octave averaged BRL (BRLA) by more than 10 dB at 1600 Hz for grazing angles above 20°. This results in a frequency inversion since, at lower frequencies, the effect of the layering is much smaller; at 50 Hz there is almost no effect. An important feature of this dramatic decrease in BRLA is its relative independence from the details of the layering structure. However, the exact nature of the layering does have an important effect on BRL and the phase of R at a single frequency, and on BRLA at about 800 Hz. Studies of an artificial layered structure made up of equally spaced, identical layers show that the physical process producing the decrease in BRL is a collective effect of the layered structure and is related to the constructive interference of reflections from each of the layers.

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I. INTRODUCTION

Acoustic interaction with the ocean bottom can be an important factor influencing the propagation of sound waves in the ocean. This is particularly true at low frequencies where significant energy penetrates deeply into the subbottom and interacts with the subbottom structure. For a horizontally stratified, unlayered (but possibly depth dependent), deep sea sediment, the major bottom interaction processes influencing low frequency propagation are: reflection from the water-sediment interface, refraction of energy penetrating into the sediment, compressional wave absorption within the sediment, and sediment shear wave excitation and absorption. Interface wave propagation along the substrate interface and scattering from rough interfaces may also be important processes for some frequency ranges.

For a thick, uniform, deep sea sediment layer, reflection from the water-sediment interface dominates the bottom interaction at high frequencies and high grazing angles. Absorption increases with frequency,[1] so that at sufficiently high frequencies the refracted energy is totally absorbed within the sediment. Little energy reaches the substrate so that processes occurring there such as sediment shear wave excitation,[2] interface wave effects, and scattering from the substrate are negligible. Scattering from the water-sediment interface is negligible at low frequencies for the clay and silt sediment types typically found in deep sea environments.[3]

Actual marine sediment structures are considerably more complicated than a single uniform layer overlying a substrate. The sources of sedimentation, the chemical and physical processes that occur within

the sediment, and local erosional processes result in abrupt changes in sediment properties (layering) in addition to the smooth depth dependence of sediment acoustic parameters. Coring[4,5] and acoustic profiling[6,7] show that layers with thicknesses from less than a millimeter to greater than 500 m occur in marine sediments.

Some acoustical effects of small scale layering have been reported. Careful seismic profiling, accompanied by local coring measurements, has implicated multiple reflections from near-surface layering as the cause of anomalously large returns interpreted as being from deep reflectors.[6] Other work[8] has suggested layering as the cause of frequency inversion in measured octave averaged bottom loss in which lower loss occurs at higher frequencies. The sensitivity of the plane wave reflection coefficient R to small scale layering has been studied numerically[9] and results indicate that the phase and magnitude of R at a given frequency depend critically on the details of the layering for frequencies above 100-200 Hz, but are relatively insensitive to them at lower frequencies.

In this paper we will discuss some additional effects of thin, near-surface layering in otherwise thick sediments on the reflectivity of the ocean bottom. Both continuous wave (cw) and 1/3 octave averaged bottom reflection loss, BRL = $-20 \log_{10}(|R|)$, and the cw bottom reflection phase shift will be examined for both artificial and geologically realistic layering structures.

Several important results are obtained. At higher frequencies a resonance type phenomenon reduces 1/3 octave averaged BRL at high grazing angles by about 15 dB at 1600 Hz. This significant reduction in BRL is fairly insensitive to the details of the layering. It is a

multilayer effect, i.e., reflection from the top few layers is not sufficient to produce the loss. In agreement with prior work,[9] low frequency (<200 Hz) cw BRL and phase shift are not greatly influenced by the relatively fine layering, but at high frequencies (>200 Hz) both are very sensitive to the exact layering structure.

The procedure used to examine the effect of subbottom layering is to compute BRL for both a layered and a smooth (reference) geoacoustic profile. One third octave averaged BRL, cw BRL, and cw phase shift are then compared for the smooth and layered structures to determine the effect of the layering. The numerical BRL model used, BOTLOSS, has been described in detail elsewhere.[10] It numerically integrates the wave equation for pressure and hence includes all wave theory processes. The basic limitation of this model is the assumption that the sediment can be treated as a fluid.

The assumption of a fluid sediment appears to be valid for the purpose of this study. Low shear wave velocities found in the upper regions of marine sediments[1] suggest that the near-surface regions can be treated as a fluid and previous work,[2] showing shear wave excitation at the water-sediment interface to be negligible, further supports this assumption. The solid properties of the sediment are important whenever significant compressional wave energy interacts with the substrate and generates shear waves in the sediment.[2,11] For the frequencies used in this study (20-6000 Hz) the high shear wave absorption[1] results in total absorption of the shear waves generated at the substrate interface before they can interact with the near-surface layering. This means that the solid properties of the sediment near the substrate act only

as an additional loss mechanism reducing the amount of energy reflected from the substrate. This affects the details of the interference between the specularly reflected and the refracted energy, but will not have a major impact on the object of our study, i.e., effects strictly related to near-surface layering.

The remainder of this paper is organized as follows. Section II examines an artificial structure consisting of identical layers with equidistant layer spacing and periodically modified spacing. Section III treats a realistic layered structure and examines changes due to random modifications of this structure. Section IV contains our conclusions.

II. ARTIFICIAL STRUCTURES

In this section BRL and the phase of R will be examined for an idealized sediment structure in which reflections are produced by abrupt changes in sound speed and density. A structure with equidistant layers is treated first and shows a resonance effect that is responsible for greatly increasing the reflectivity at certain frequencies. A slight modification in the equal spacing is then examined to show the effect on the reflectivity of altering the exact resonance conditions.

A. Equidistant layers

The artificial sediment has a total thickness of 500 m, and Fig. 1 shows the sound speed profile for the upper 15 m. There are 24 identical layers having triangularly shaped sound speed profiles with peak velocity of 1610 m/sec. The thickness of a layer at the base of its profile is 40 cm and the layers are 50 cm apart, which is about 1/2 wavelength at 1600 Hz. The sound speed profile between layers is a constant 1527 m/sec. Below the last layer the sound speed increases

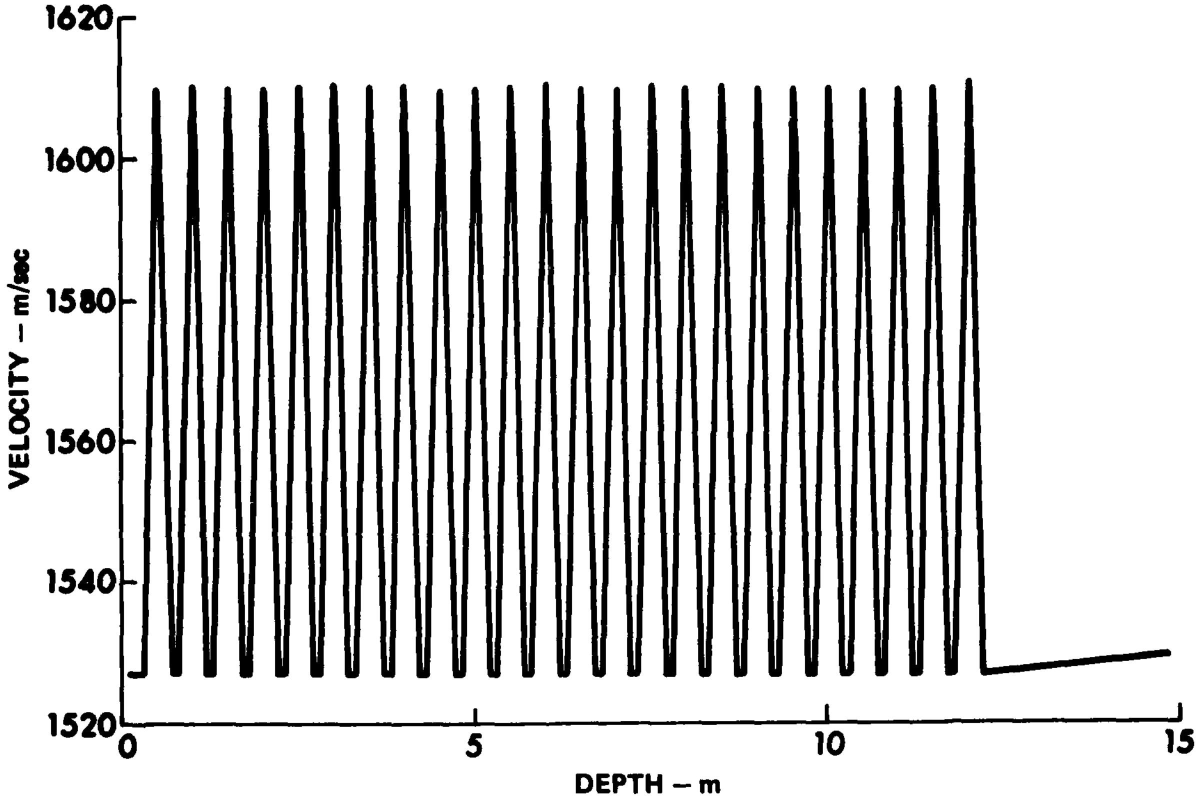

Fig. 1. Sound speed profile for 24 equidistant, identical layers.

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Fig. 1
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smoothly with a constant gradient of 1 sec^{-1}. The sediment density profile for the layered structure is also triangularly shaped: 1.27 g/cm^3 between layers and a peak value of 1.52 g/cm^3 at the center of a layer. Between layers and below the layers the density is a constant 1.27 g/cm^3. The compressional attenuation is a constant 0.0057 dB/m/kHz over the entire sediment. Bottom water parameters used in the computation are: sound speed of 1540 m/sec and density of 1.053 g/cm^3. Substrate parameters are: density of 2.6 g/cm^3, compressional velocity of 5700 m/sec, compressional attenuation of 0.03 dB/m/kHz, shear velocity of 2700 m/sec, and shear attenuation of 0.1 dB/m/kHz. For the reference (smooth) profile, the layer values are replaced by the constant velocity (1527 m/sec) and density (1.27 g/cm^3) found between layers; the rest of the profile is identical to the layered profile.

Additional calculations, not presented here, show that, for the frequency ranges studied, triangular and rectangular layer profiles of equal "area" produce essentially the same effect on calculated BRL. (Here equal "area" means that the rectangle height is the same as that of the triangle and its thickness is half the triangle thickness at its base, i.e., thickness of 20 cm, peak velocity of 1610 m/sec).

Figure 2 shows the frequency dependence of near normal incidence BRL for both the artificial layered profile and the smooth profile. BRL for the smooth profile (dashed curve) has the expected rapid oscillatory behavior due to the interference between the energy reflected from the water-sediment interface and that reflected from the substrate. A simple calculation using an average sound speed of 1780 m/sec shows

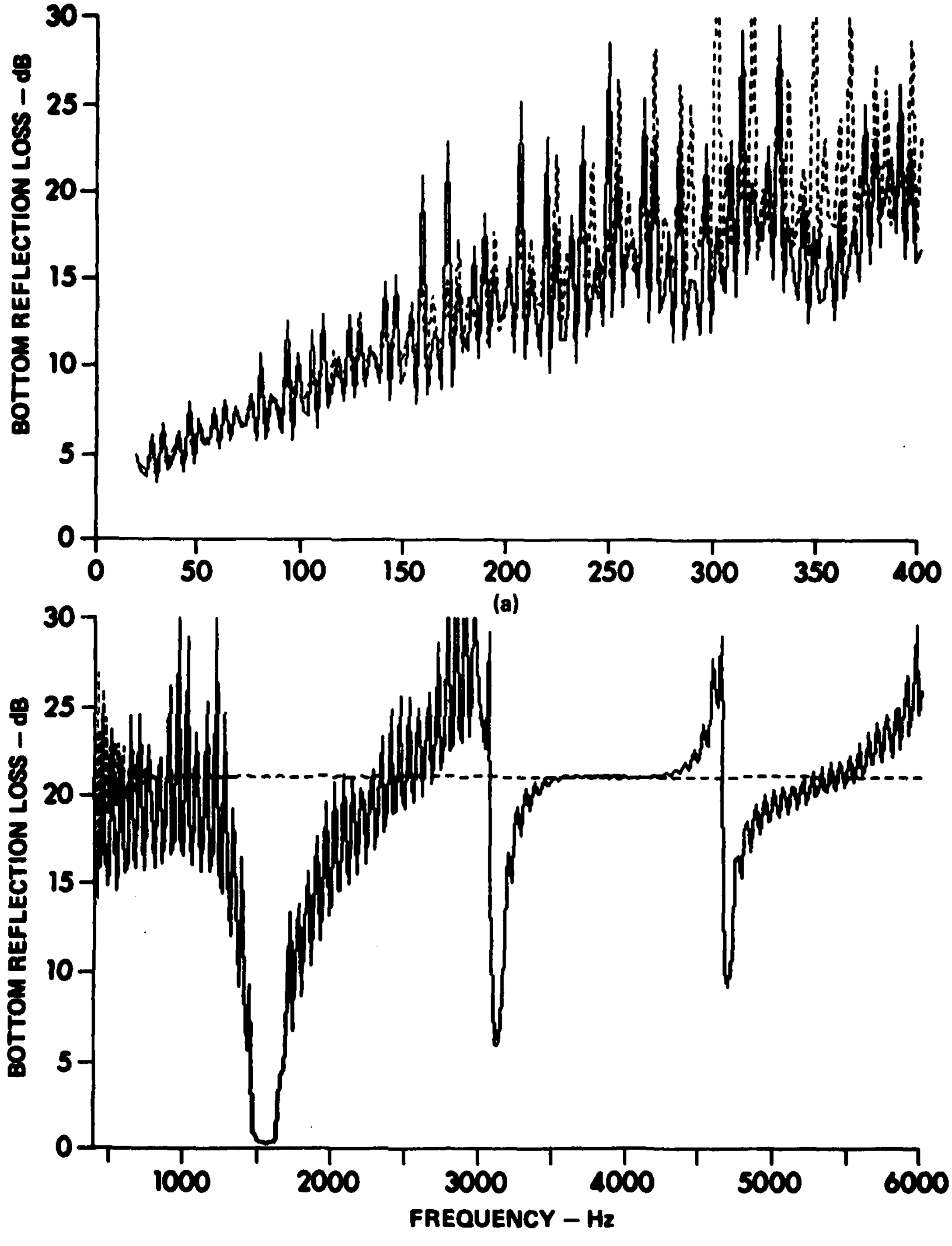

Fig. 2. A comparison of near normal incidence (88°) BRL from the equidistant layered profile (solid curve) and the smooth reference profile (dashed curve): (a) 20-400 Hz, (b) 400-6000 Hz.

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that a frequency increment of about 2 Hz is needed for a phase shift of 2π. This estimate is verified by a high resolution computation in the frequency interval 20-40 Hz, which shows a recurrent oscillatory structure with a 1.78 Hz spacing between peaks. The actual structure seen in Fig. 2(a) has about 6 Hz between peaks. This is an undersampling artifact due to the 2.5 Hz frequency increment used to generate Fig. 2(a). (For Fig. 2(b) the frequency increment is 7.5 Hz between 400-600 Hz and 20 Hz between 600-6000 Hz.) The oscillations in the smooth profile curve disappear above about 800 Hz and a constant level of about 21 dB persists out to 6000 Hz. This limiting value agrees with that computed from the normal incidence reflection coefficient. At 800 Hz the attenuation is about 46 dB for a wave traveling through the 500 m sediment and back to the surface. The amplitude of this reflected wave is at least 25 dB (ratio of about 0.1) below that of the wave reflected from the sediment surface. Only a small interference effect can occur and hence above 800 Hz the increasing attenuation results in the sediment penetrating energy being negligible.

For the layered profile (solid curve), Fig. 2 shows two new features in the frequency dependence of near normal incidence BRL. Rapid oscillations due to basement reflected energy still occur below 800 Hz as in the smooth profile case. The first new feature is a modulation of the rapid oscillations in Fig. 2(a), beginning at about 65 Hz, with a period of about 65 Hz. It is most clearly visible in the locations of the BRL minima and continues in the higher frequencies (solid curve in Fig. 2(b)). The second and most distinctive new feature is the occurrence of very deep minima in BRL (very high reflectivity) near

1600, 3200, and 4800 Hz. The minimum near 1600 Hz is particularly low with a value near 0.5 dB.

These new features introduced by the near-surface layering can be qualitatively understood and related to some simple properties of the geoacoustic profile. Wavelengths that are large compared to an individual layer will average over the sound speed profile and, for low frequencies, the upper 12 m will appear to be a homogeneous layer with a sound speed of about 1560 m/sec. Reflection from the bottom of this layer at 12 m would give a periodic (in frequency) oscillation in BRL with a period of 65 Hz, essentially the period of the observed modulation. Attenuation in the top 12 m will terminate this modulation at about 30 kHz and, as seen in Fig. 2(b), this oscillation persists to at least 6 kHz.

The deep minima in BRL can be identified with a collective resonance interference effect from the equidistant layers similar to that responsible for enhanced reflectivity in periodic optical coatings.[12] The layered structure is made up of a series of identical cells 50 cm thick. If the reflected fields from two cells are in phase at the sediment surface at a frequency f_o, they will also be in phase at $f_o+\delta f$, where δf is the frequency increment necessary to add 2π to the phase accumulated in passing through a cell and back; i.e., at frequencies for which the cell is an integer number of half wavelengths thick. Since the interface reflection and transmission coefficients are independent of frequency, δf is related only to propagation through a cell. Using an average sound speed of 1560 m/sec, $\delta f = 1560$ Hz, which agrees well with the observed 1600 Hz spacing between minima. The increased reflectivity regions will recur

at higher frequencies but with decreasing effectiveness as attenuation reduces the effect of the lower layers. Eventually the attenuation within a single cell will increase enough to eliminate collective interference effects from the layers.

The effect of the layering on frequency averaged BRL is shown in Table I where 1/3 octave averaged BRL (BRLA) is compared at several frequencies for smooth and layered profiles. The frequency averaging was done by converting BRL to $|R|$, averaging $|R|$ from $2^{-1/6}f_o$ to $2^{1/6}f_o$, then converting back to BRL. Again, the effect of layering is small at low frequencies, but it is apparent at 250 Hz, where the modulation structure seen in Fig. 2(a) contributes about a 3 dB decrease. At 1600 Hz the layered structure produces a dramatic decrease in BRLA to 2.6 dB compared to the limiting value of 21 dB for the smooth structure. The major decrease in cw BRL seen in Fig. 2(b) persists in the 1/3 octave average.

Table I also indicates that near-surface layering can result in a pronounced frequency inversion in BRLA. For the smooth profile BRLA increases monotonically with frequency to a constant value of 21 dB. Figure 2 shows that BRLA for the layered profile has a pronounced frequency inversion between 500 and 1600 Hz, i.e., BRLA at 1600 Hz will be significantly lower than that at 500 Hz. Figure 2 also indicates that the inversion is very pronounced between about 1 and 1.6 kHz. As indicated in Table I the resonance near 3200 Hz produces a much smaller reduction in BRLA and hence a weaker frequency inversion.

TABLE I. 1/3 octave averaged bottom reflection loss for smooth and layered artificial profiles.

Center Frequency (Hz)	Smooth BRLA (dB)	Layered Profile BRLA (dB)
50	5.9	5.8
100	8.6	8.1
250	15.7	14.2
500	20.6	17.1
1600	21.0	2.6
3200	21.0	14.4

Figure 3 shows the phase shift introduced by near-surface layering. Qualitatively the phase shift has the same structure as the BRL in Fig. 2, i.e., near-surface layering has little effect (±10°) on the phase shift up to about 150 Hz. Above 150 Hz much larger changes, up to ±180°, can occur. Near 1600 Hz a gradual phase shift of nearly 180° occurs. This is reminiscent of phase shifts found in resonant systems and supports our identification of a collective resonance effect as the cause of the BRL minima.

Several conclusions can be drawn from Figs. 2 and 3. First, at sufficiently low frequencies the near-surface layering has almost no effect on BRL. Second, at the frequencies associated with the layer spacing a resonantly enhanced reflectivity occurs, resulting in dramatically lower BRL. Third, the near-surface layering can produce pronounced frequency inversions in frequency averaged BRL. Fourth, near-surface layering can significantly affect the bottom reflection phase shift.

B. Almost equidistant layers

A second artificial profile was examined to determine whether an exactly periodic structure is needed to produce the strongly enhanced reflectivity near 1600 Hz. The layer shape and geoacoustic parameters are the same as for the equidistant profile, but the center points of the layers are changed from the positions shown in Fig. 1. The center points of the first four layers are shifted by 0.0 cm, -7.0 cm, +2.0 cm, and +5 cm, respectively. This set of displacements was then repeated in the same order for the remaining 20 layers.

Figure 4 shows that the modified structure still produces a large reduction in BRL at 1600 Hz, and the curve retains the 65 Hz oscillation

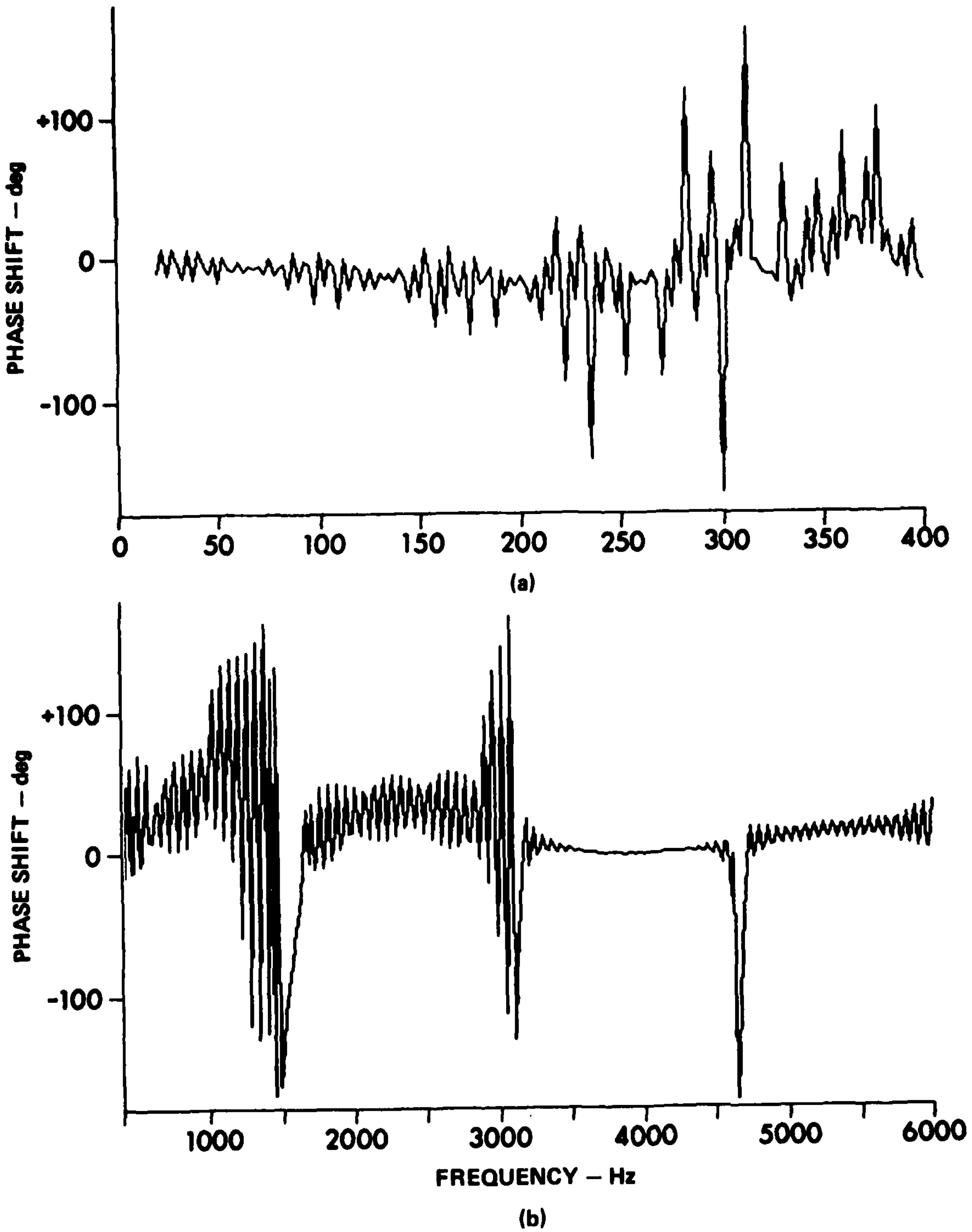

Fig. 3. The phase shift at 88° produced by the equidistant layered profile relative to that produced by the smooth reference profile: (a) 20–400 Hz, (b) 400–6000 Hz.

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Fig. 3
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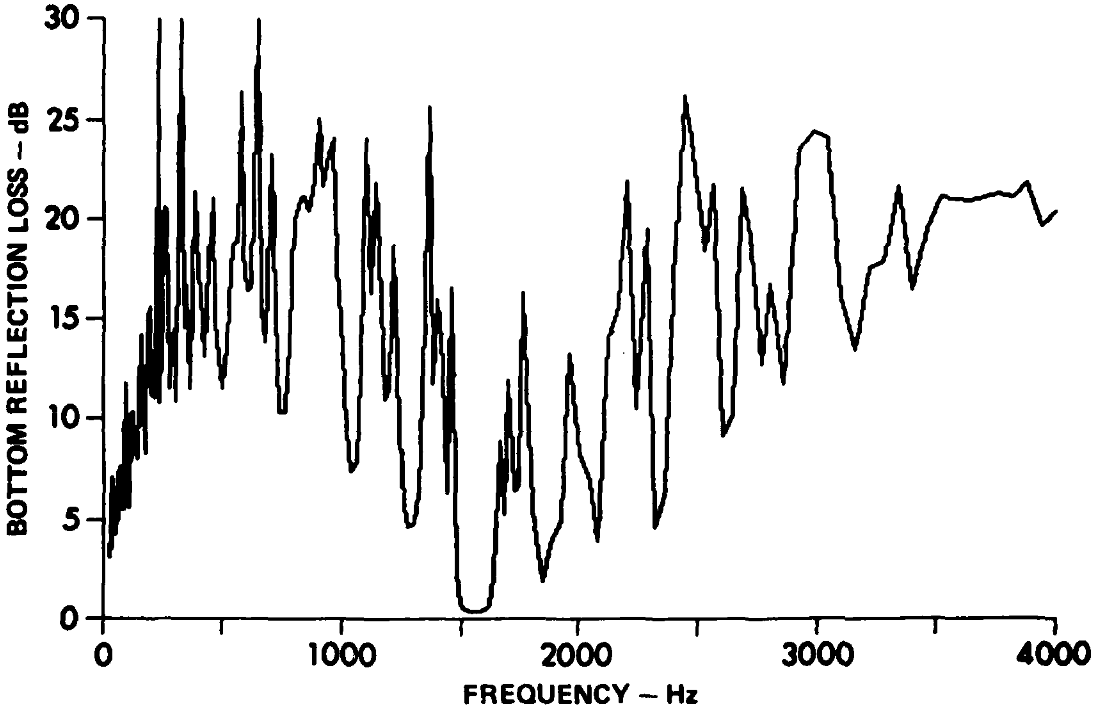

Fig. 4. Near normal (88°) incidence BRL for the modified artificial profile.

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Fig. 4
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noted in Fig. 2(a). The BRLA is 14.9 dB at 500 Hz, 3.1 dB at 1600 Hz, and 17.3 dB at 3200 Hz. These values deviate from the equidistant case but are not consistent in magnitude or sign. However, the frequency inversion is clearly visible from 500 Hz to 1600 Hz. Evidently the process producing the increased reflectivity at 1600 Hz does not require an exactly periodic structure.

To identify the depth at which the increased reflectivity near 1600 Hz is being produced, two truncated versions of the modulated artificial profile were used. In the first only the top 12 layers are used, while in the second only the bottom 12 layers are used.

Figure 5 shows the frequency dependence of near normal incidence BRL for the profile using the top 12 layers. The same general features occur here as in the 24-layer case. In particular, the resonance dip near 1600 Hz is still very deep; BRLA at 1600 Hz is 3.4 dB compared to 3.1 dB in the 24-layer case. Comparison with Fig. 4 shows that most of the increased reflectivity is occurring in the top 12 layers, and the addition of the lower 12 layers decreases BRLA by only 0.3 dB. However, as seen below, this does not mean that the structure below 6 m can be neglected.

Figure 6 shows the frequency dependence of near normal incidence BRL for the profile using only the bottom 12 layers. Again the same qualitative features observed in the 24-layer case occur. In this case the resonance dip near 1600 Hz is not as deep; BRLA at 1600 Hz is 4.35 dB. The 0.95 dB increase relative to the upper 12-layer case agrees well with the additional attenuation of 1.1 dB (at 1600 Hz) occurring in the upper 6 m of isovelocity sediment.

Some general conclusions can now be drawn about the process governing the resonance decrease in BRL. First, the layers need not

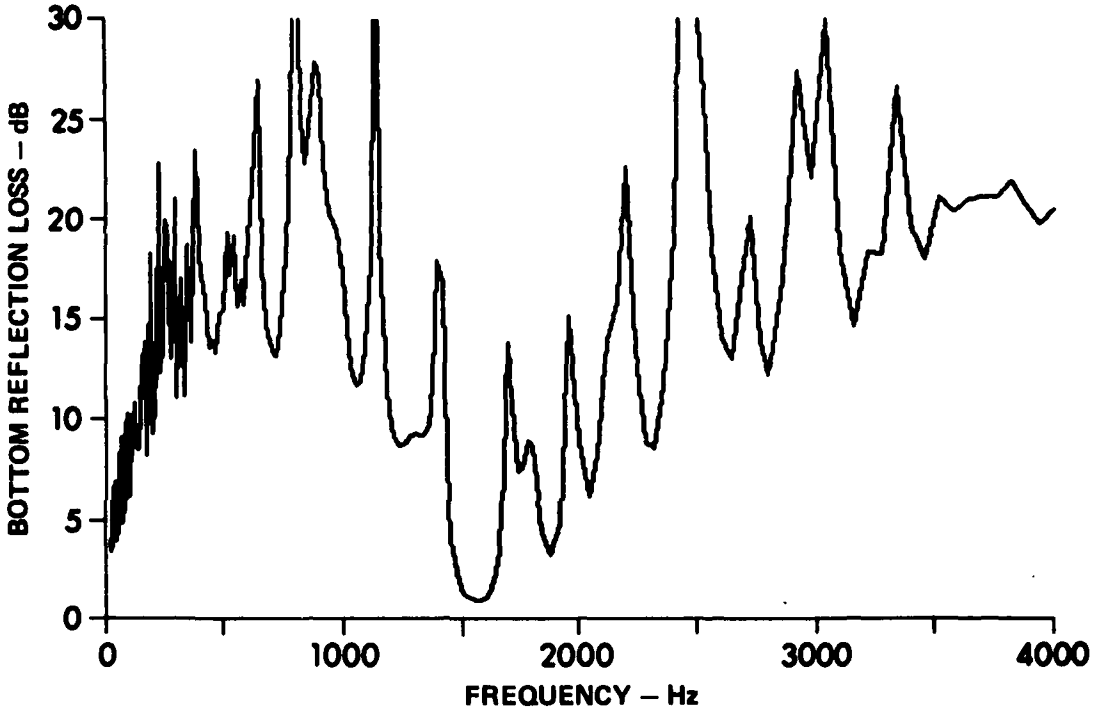

Fig. 5. Near normal incidence (88°) BRL from the upper 12 layers of the modified artificial profile.

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Fig. 5
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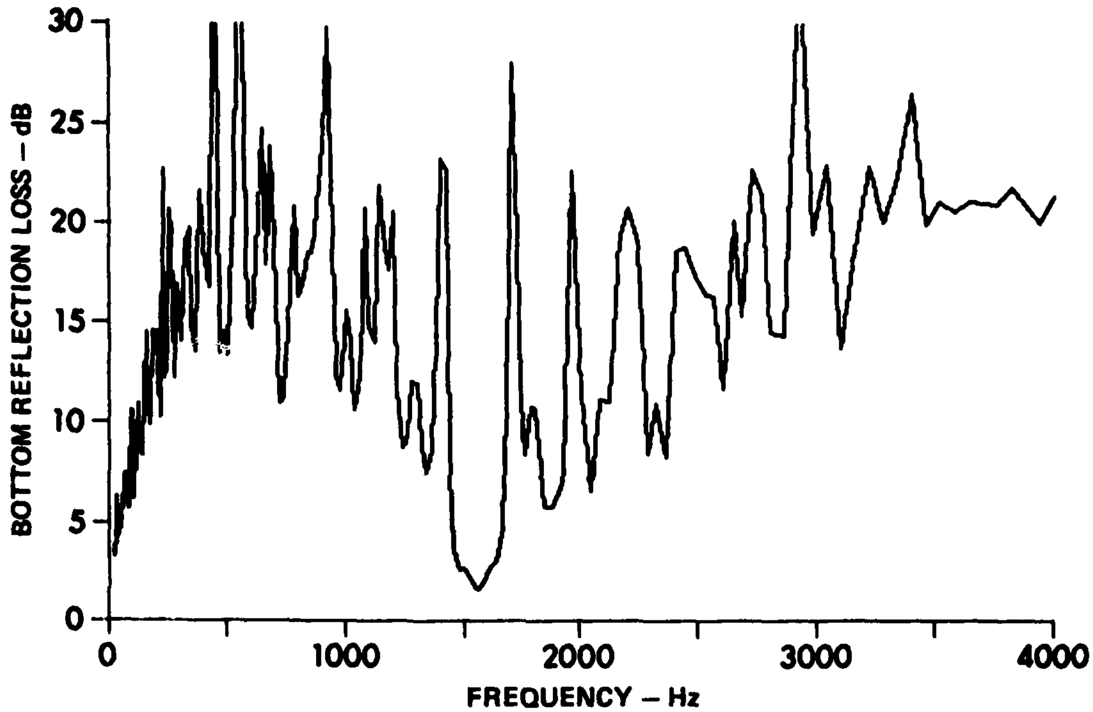

Fig. 6. Near normal incidence (88°) BRL from the lower 12 layers of the modified artificial profile.

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Fig. 6
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be equidistant; slight variations from an equal spacing do not significantly affect the occurrence of the resonance. Second, reflection from an upper sequence of layers decreases the effect of lower layers. This is due to the small amount of energy penetrating to the lower layers. Finally, sediment attenuation in an overlying uniform section of sediment limits the magnitude of the resonance effect occurring in a deeper layered section.

III. REALISTIC NEAR-SURFACE LAYERING

The purpose of this section is to illustrate some of the effects produced by realistic near-surface layering in an otherwise thick, uniform sediment structure on BRL, BRLA, and the phase of R. The dependence of calculated BRL on grazing angle at frequencies from 25-1600 Hz will be compared for layered and smooth geoacoustic profiles. The objective will be to show that major decreases in BRLA, on the order of that seen for highly regular layer spacing at near normal incidence, can result from layering naturally occurring in marine sediments.

A. Geoacoustic profile

For this study realistic geoacoustic profiles for near-surface layering were developed from recently published data of Tucholke and Shirley.[4] They reported measurements of the physical and acoustical properties of three closely spaced (<12 km) locations in the western Nares Abyssal Plain (cores RC19-20, RC19-21, and RC19-22). They identified geological features, which were traced from core to core, and defined several similar zones. Local depositional and erosional patterns resulted in varying zone thicknesses and numbers of layers within a zone. Table II is a compilation of some average properties of seven such zones.

TABLE II. Average properties of seven near-surface zones.

Zone	Thickness (m)	Number of Layers	Layer Separations (m)	Layer Porosity (%)
1	2.5	5	0.43	68
2	1.9	0	---	75
3	1.5	1	---	60
4	0.3	2	0.20	64
5	2.3	3	0.64	57
6	0.4	0	---	75
7	2.0	2	1.40	50

The geoacoustic parameters of individual layers are obtained from their porosity using empirically determined relationships. Attenuation is estimated from published curves[2] but biased toward lower values at high porosities due to recent measurements.[6,13] Density and the ratio of sediment sound speed to water sound speed are obtained from the porosity using tabulated data[14] for abyssal plains environments; the values at 50% porosity were taken from tabulated data[14] for continental terrace environments. The reported bottom water velocity[4] of 1560 m/sec was used to convert the velocity ratio to in situ velocity.

Tables II and III were used to develop the sound speed profile shown in Fig. 7. The background sediment between layers is homogeneous with a porosity of about 80%. The upper 12 m contains 13 layers compared to the 24 layers in our artificial structure (Fig. 1). Below the last layer the sound speed gradient is 1 sec^{-1} and the density gradient is 1.4×10^{-3} $g/cm^3/m$. The profile terminates at 500 m. In the reference smooth profile, the layers are replaced by the homogeneous background sediment.

B. Typical results

At low frequencies the effect of layering on calculated BRL is very small. Figure 8 compares the dependence on grazing angle of both BRL and BRLA at 50 Hz; the results for both layered and smooth profiles are nearly identical. However, the 1/3 octave frequency averaging in BRLA smooths out the BRLA plots compared to the oscillations seen in the BRL plots. The effect on the phase of R is noticeable (Fig. 9) but is generally small.

TABLE III. Geoacoustic parameters of near-surface layers.

Porosity (%)	Sound Speed (m/sec)	Attenuation (dB/m-kHz)	Density (g/cm^3)
50	1592	0.63	1.86
57	1578	0.55	1.65
60	1573	0.40	1.63
64	1565	0.20	1.60
68	1558	0.05	1.55
75	1545	0.03	1.44

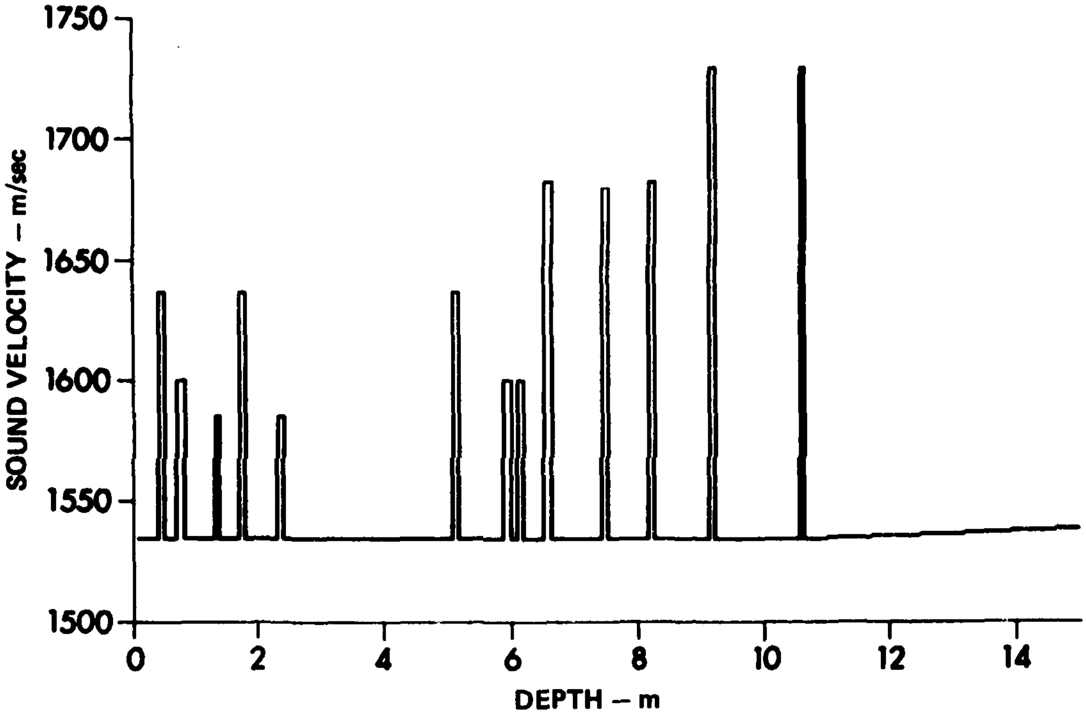

Fig. 7. Realistic sound speed profile for the top 12 m of sediment.

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Fig. 7
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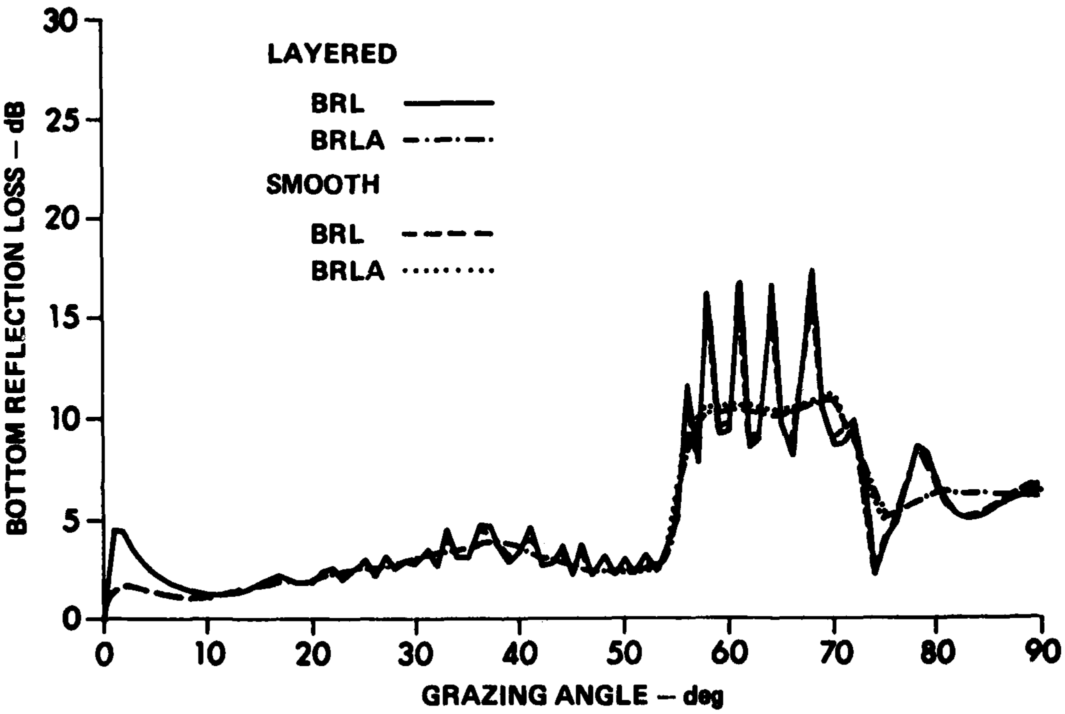

Fig. 8. A comparison at 50 Hz of BRL and BRLA produced by the realistic layered profile and the smooth profile.

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Fig. 8
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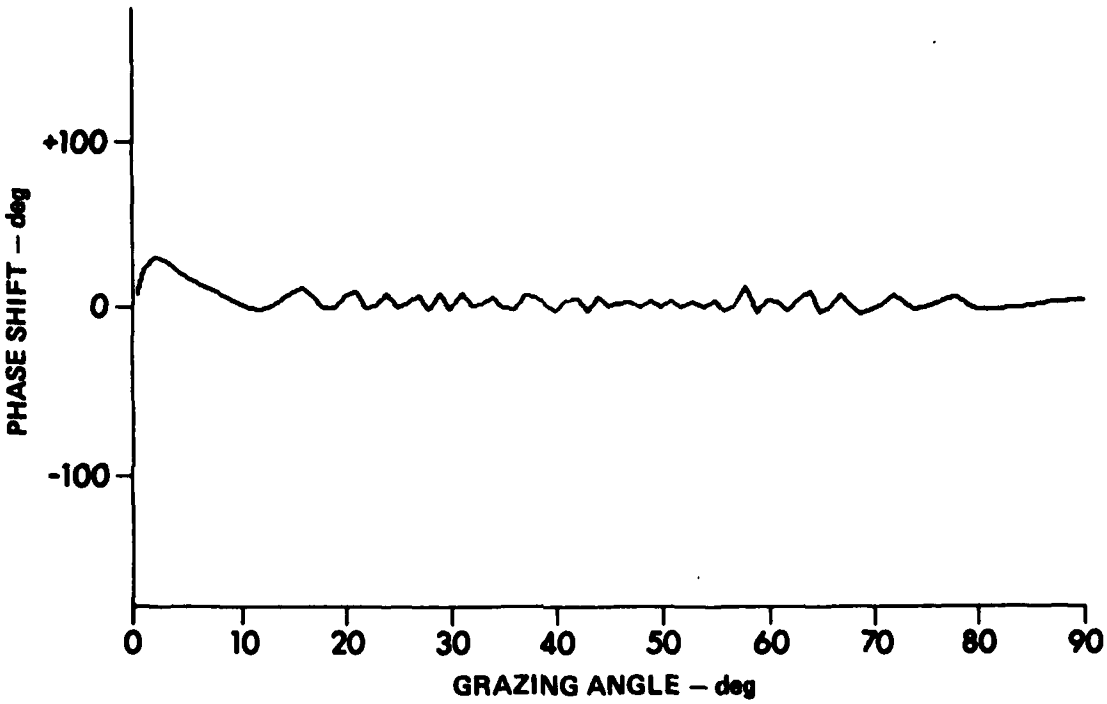

Fig. 9. The phase shift at 50 Hz produced by realistic near-surface layering relative to that produced by a smooth profile.

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Fig. 9
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As frequency increases, the effect of the layering becomes noticeable. At 200 Hz (Fig. 10) definite changes in BRL and BRLA can be seen with a maximum decrease in BRLA of about 3 dB. The change in cw phase (Fig. 11) can be quite large in the vicinity of certain grazing angles.

At 800 Hz Fig. 12 shows that the near-surface layering produces a significant reduction in both BRL and BRLA. Above 15° BRL from the layered profile is from 4 to 8 dB lower than from the smooth profile. The smoothing effect of frequency averaging is clearly evident. BRL for the layered profile clearly has more severe oscillations than the smooth profile. This is due partly to the increased attenuation of the refracted energy in the smooth profile case and partly to the mutual interference of the partial reflections from the near-surface layering in the structured profile. Figure 13 shows that the near-surface layering has an important effect on the phase of R at this frequency.

At 1600 Hz the layered profile produces the dramatic reduction in BRL shown in Fig. 14. For the smooth profile, BRL and BRLA are nearly identical; the bottom penetrating energy is completely absorbed and BRL is given by the frequency independent reflection coefficient of the water-sediment interface. Above 40° BRL is 18.5 dB, the value given by the reflection coefficient of the water-sediment interface at normal incidence. However, the BRL plot for the layered profile shows considerable structure in angle. BRLA for the layered profile has less angular dependence, and shows a marked reduction beyond 15° of from 6 to 14 dB; the normal incidence value is about 5 dB, a decrease of about 14 dB. Thus, the realistic layering structure used here produces the

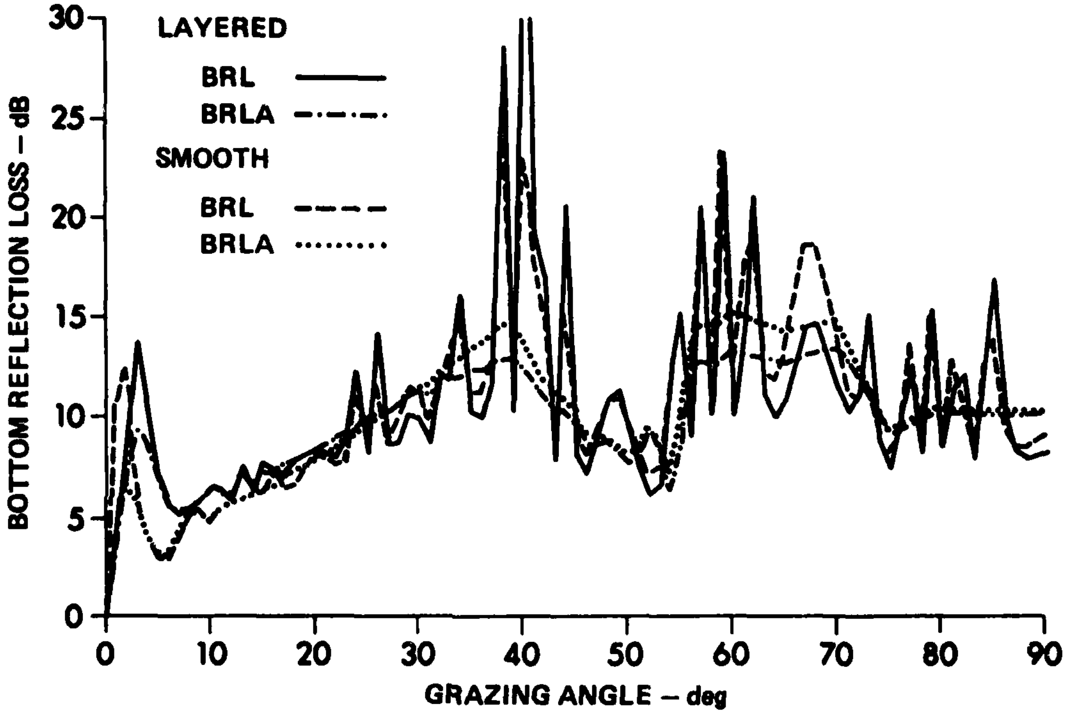

Fig. 10. A comparison at 200 Hz of BRL and BRLA produced by a realistic layered profile and a smooth profile.

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Fig. 10
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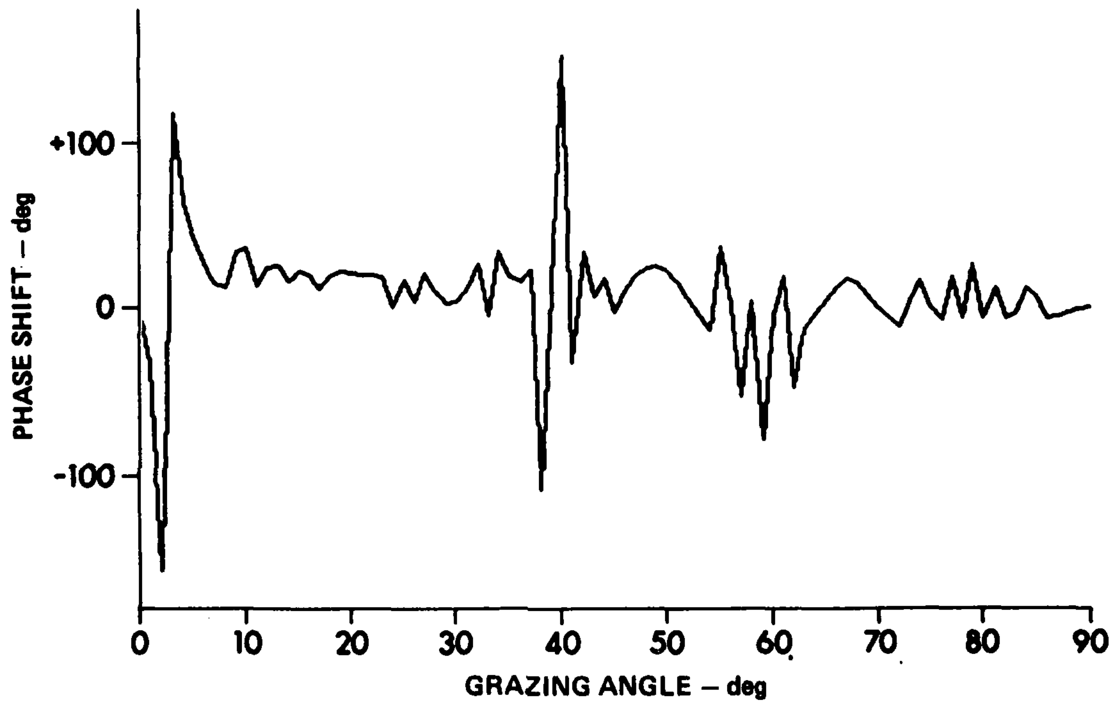

Fig. 11. Dependence on grazing angle at 200 Hz of the phase shift introduced by realistic near-surface layering relative to that of a smooth profile.

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Fig. 11
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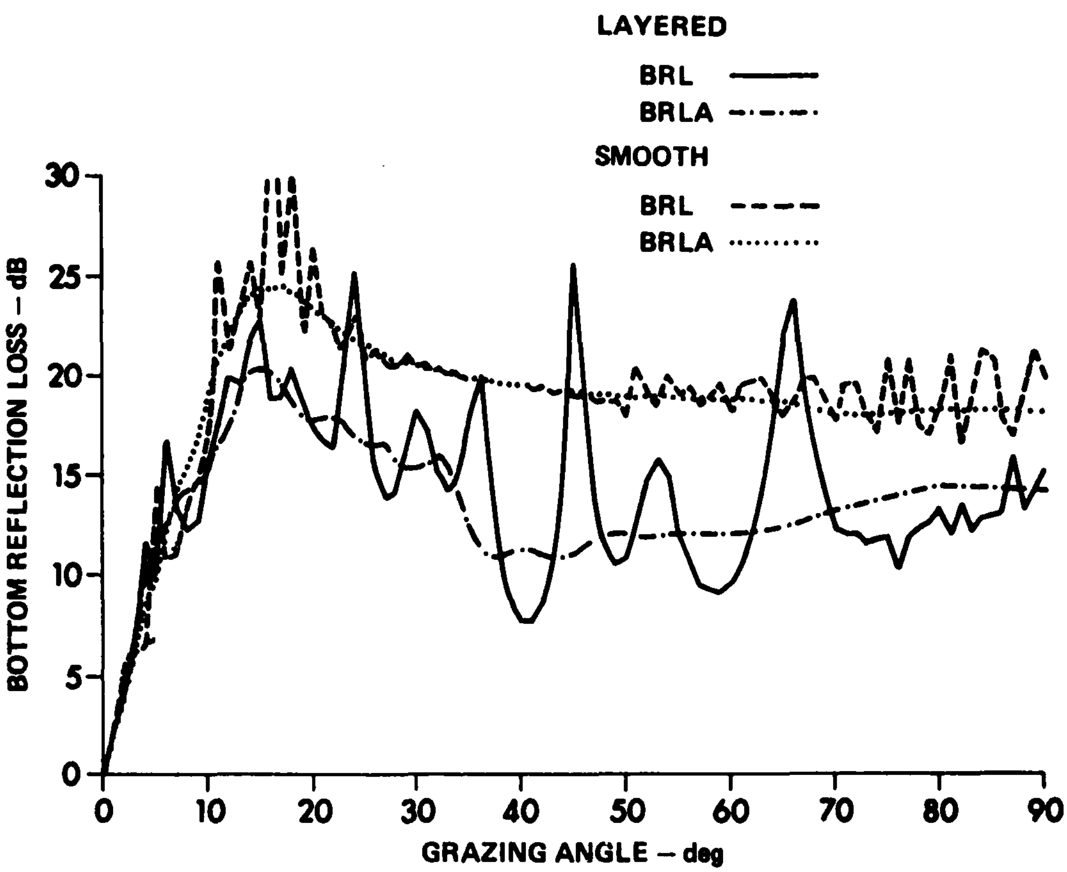

Fig. 12. A comparison at 800 Hz of BRL and BRLA produced by a realistic layered profile and a smooth profile.

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Fig. 12
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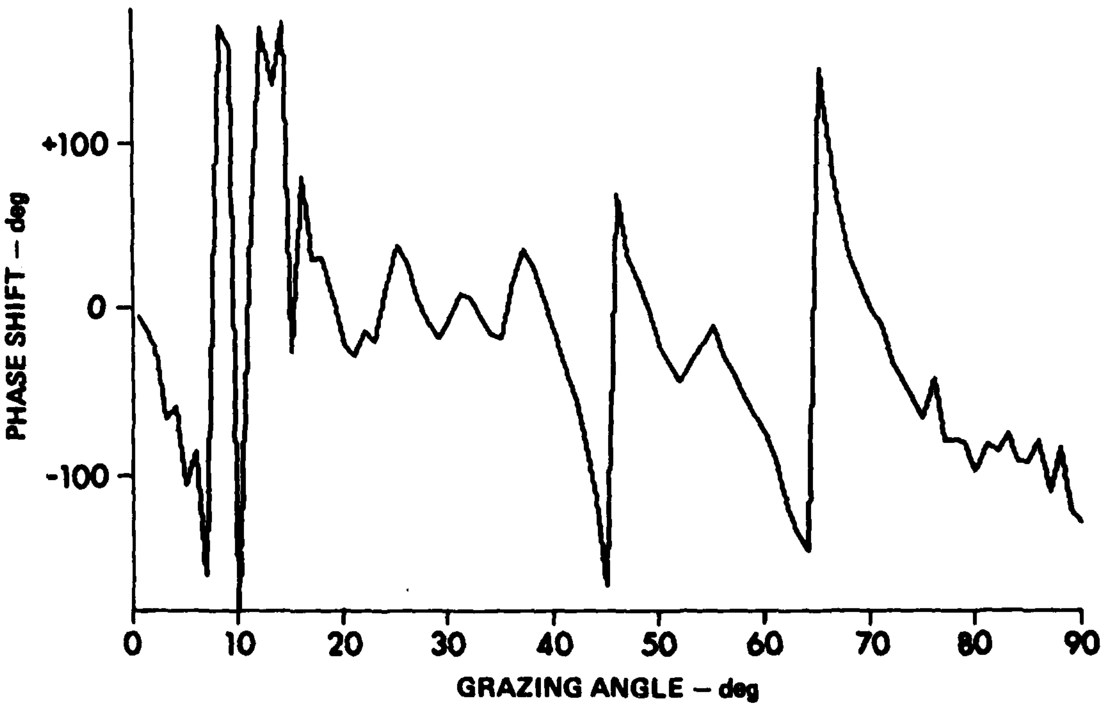

Fig. 13. Dependence on grazing angle at 800 Hz of the phase shift introduced by realistic near-surface layering relative to that of a smooth profile.

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Fig. 13
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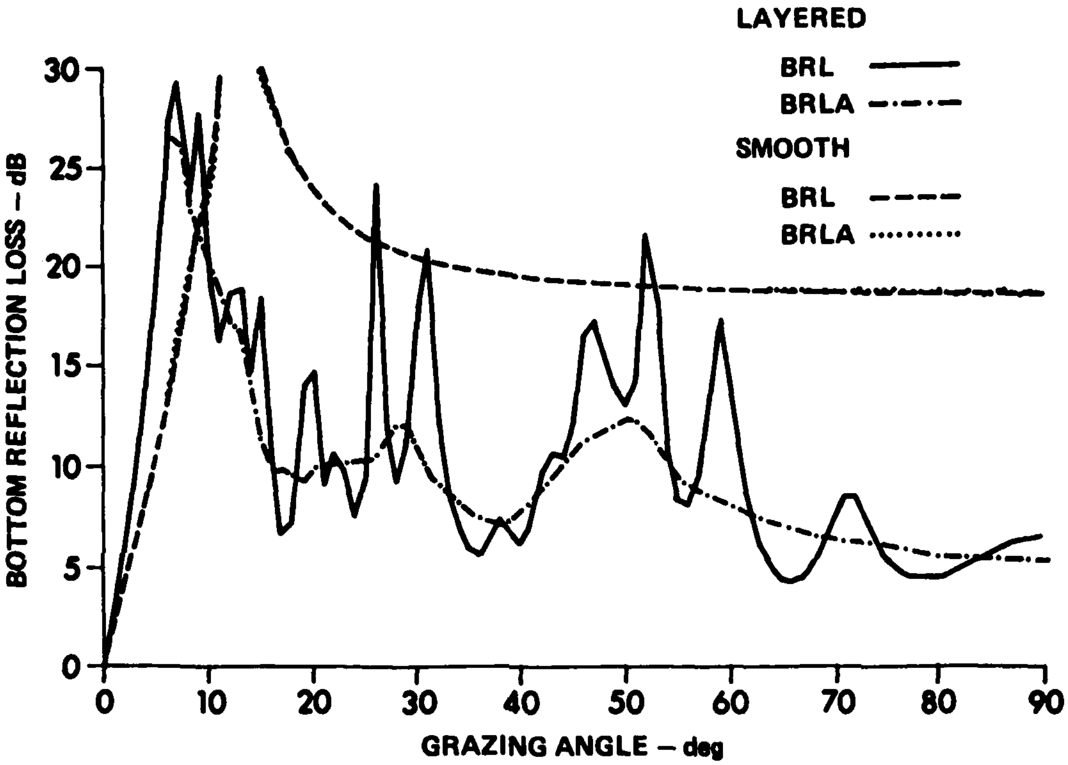

Fig. 14. A comparison at 1600 Hz of BRL and BRLA produced by a realistic layered profile and a smooth profile.

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Fig. 14
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same significantly increased reflectivity as the artificial layered structure. Figure 15 shows the extremely grazing angle dependent phase changes introduced by near-surface layering.

C. Results for different structures

An important consideration in determining if this dramatic decrease in BRLA can be observed is whether the decrease depends critically on exact spacing and layer parameters. To examine this question, three new profiles were generated by randomly changing the spacing between layers. Two additional profiles were produced by changing both the order and the spacing of the layers. All cases had 13 layers in the top 12 m. BRLA for these five profiles and the original realistic layer were compared to observe the sensitivity of BRLA to layering details.

At 800 Hz, where the reduction produced by our original layering was about 5 dB, BRLA is fairly sensitive. Figure 16 compares the results obtained from all six structures with the smooth profile result shown for reference. While all profiles produced a decrease in BRLA, the spread averages about 7 dB with a maximum of about 12 dB. At this frequency the details of the layering are clearly important.

The cw phase shift introduced by the layering at 800 Hz is shown in Fig. 17. There is little, if any, correlation in phase shift from structure to structure. The oscillatory structure of cw BRL has this same sensitivity to the layering structure. The detailed structure must be known to accurately compute BRL and the bottom reflection phase shift.

At 1600 Hz BRLA (Fig. 18) from the six layered structures cluster very nicely. Above 15° the spread averages 5 dB or less with a maximum

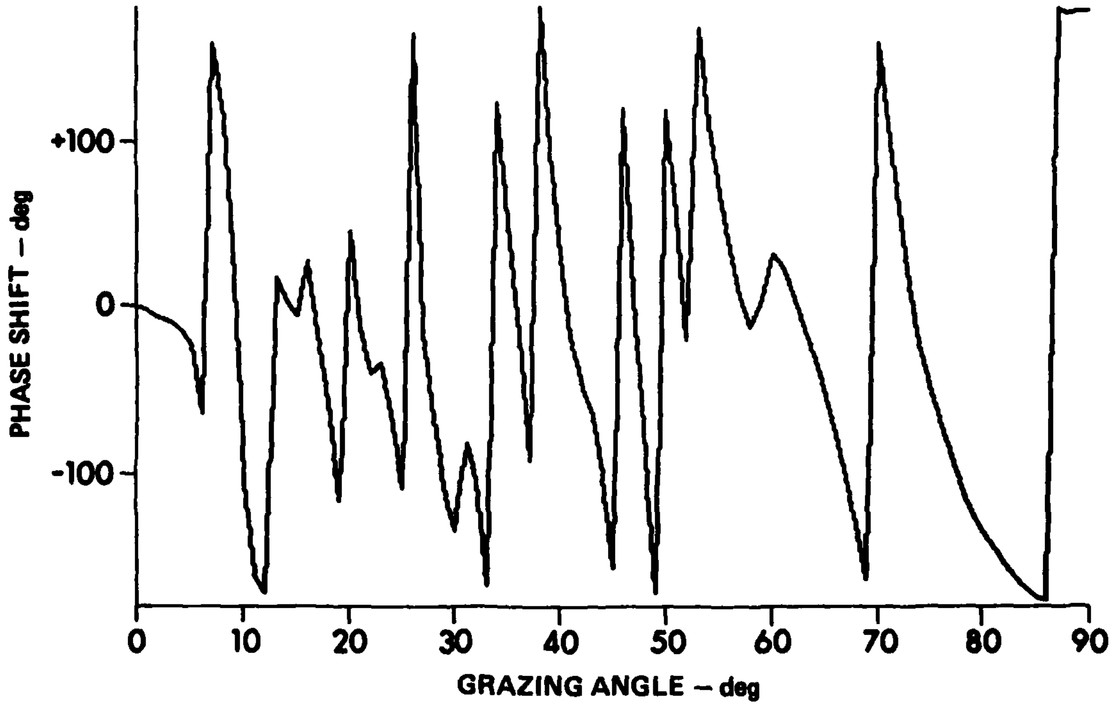

Fig. 15. Dependence on grazing angle at 1600 Hz of the phase shift introduced by realistic near-surface layering relative to that of a smooth profile.

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Fig. 15
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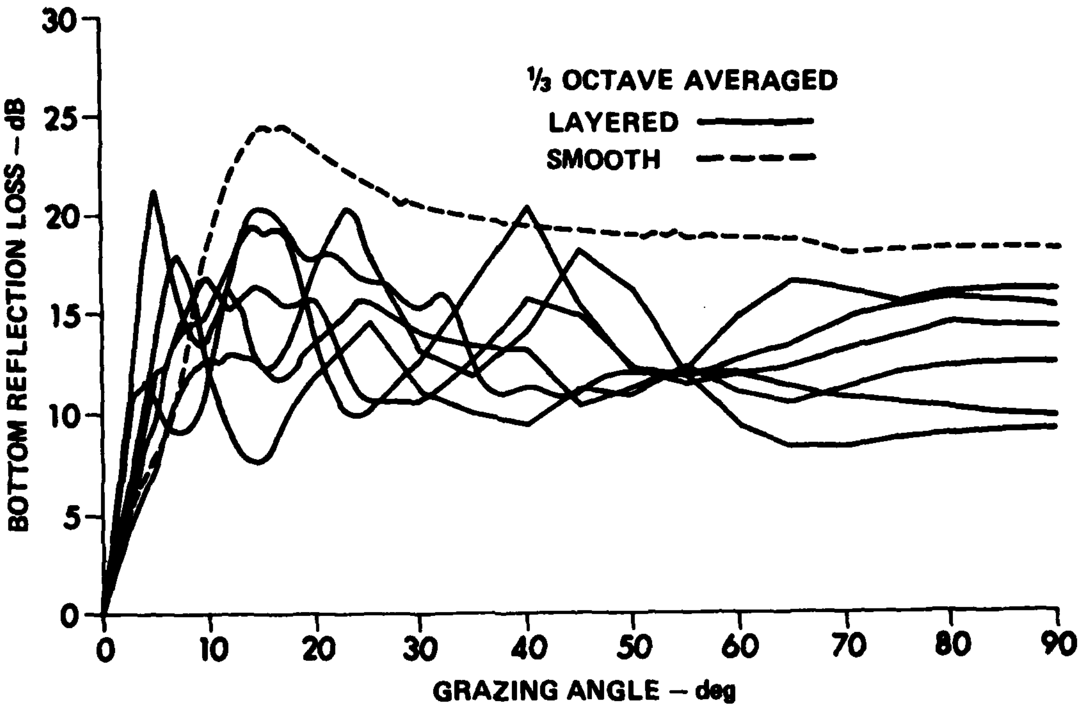

Fig. 16. A comparison of BRLA at 800 Hz for six different realistic layered profiles (solid curves) and a smooth profile (dashed curve).

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Fig. 16
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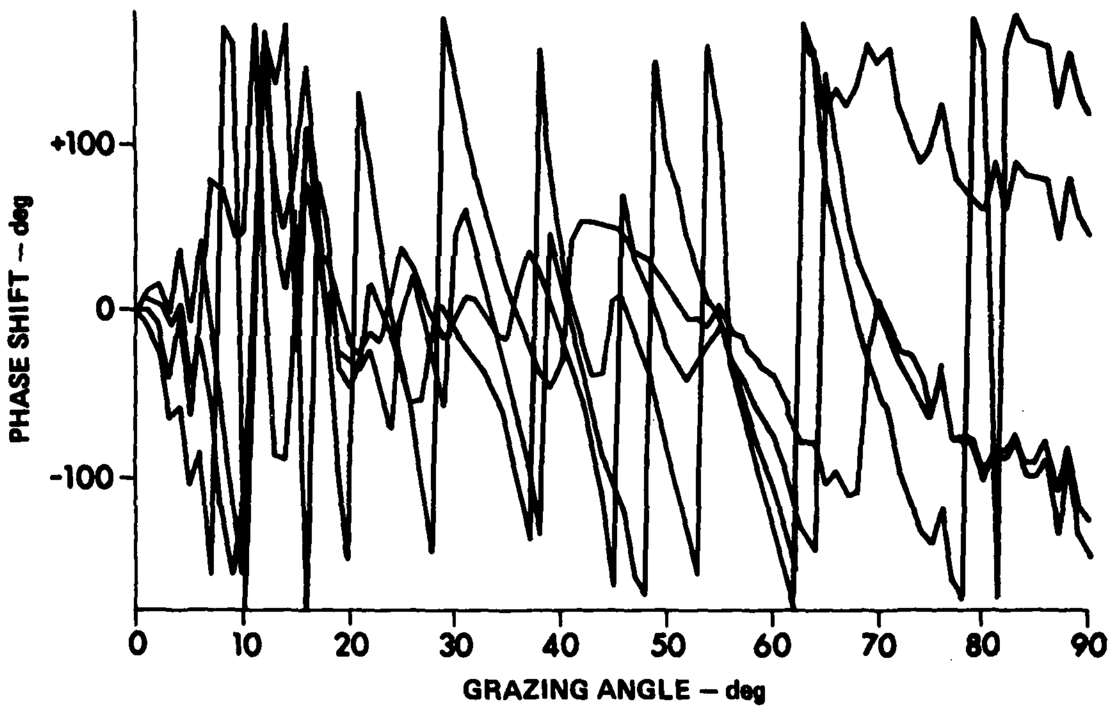

Fig. 17. Dependence on grazing angle at 800 Hz of the phase shift introduced by four different realistic layered profiles relative to that of a smooth profile.

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Fig. 17
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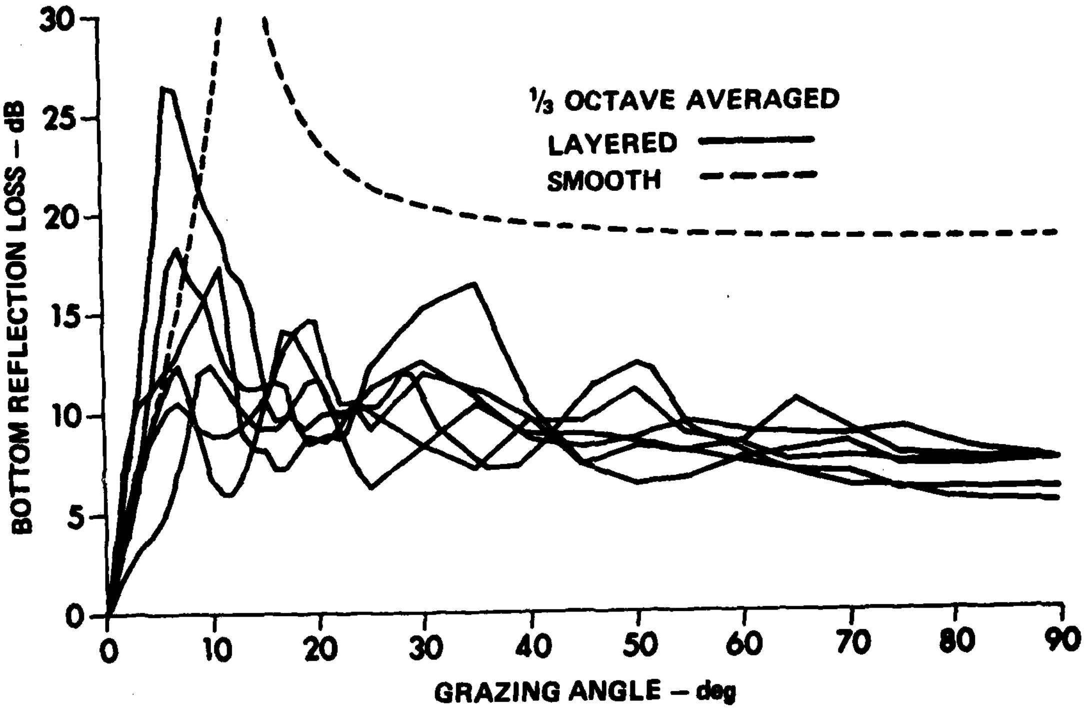

Fig. 18. A comparison at 1600 Hz of BRLA for six different realistic layered profiles (solid curves) and a smooth profile (dashed curve).

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Fig. 18
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of about 8 dB. Beyond 40° the spread is about 3 dB with a maximum of 6 dB. This spread may well become smaller for larger averaging bands, e.g., full octave. The dramatic decrease in BRLA is fairly insensitive to detailed layering, particularly for grazing angles above 40°. The cw phase shift at 1600 Hz, not shown, is similar to that at 800 Hz but has even more structure.

The reduction in BRLA at 1600 Hz results from the collective effect of the layering structure. Table IV lists BRLA produced by the top layer, the top two, the top three, and all the layers from one of the layering structures at three grazing angles. Two points should be noted. First, the additional reflection from the first layer produces about half the observed decrease at high grazing angles. Second, the effect of additional layers is not systematic. The addition of the second layer actually increases BRLA, while the third layer decreases BRLA again but not always below that produced by the first layer. The conclusion is that while the first layer can produce about half of the observed decrease, the collective effect of the entire layered structure is responsible for the remaining half.

III. CONCLUSIONS

Near-surface layering in marine sediments can have an important effect on bottom reflection loss (BRL). Computations of BRL for sediment structures 500 m thick with realistic near-surface layering show that, relative to an unlayered structure, additional reflections from the layering can reduce 1/3 octave averaged BRL (BRLA) more than 10 dB at 1600 Hz for grazing angles above 20°. This reduction is smaller at lower frequencies but is still noticeable at 200 Hz; at 50 Hz the layering has almost no effect. The lowered BRLA near 1600 Hz results

TABLE IV. Contributions of first three layers to 1/3 octave averaged BRL at 1600 Hz.

Grazing Angle (deg)	BRLA from Layer 1 (dB)	BRLA from Layers 1 and 2 (dB)	BRLA from Layers 1, 2, 3 (dB)	BRLA from All Layers (dB)
25	19.7	20.2	18.0	12.4
75	12.1	14.9	13.4	7.4
90	12.5	14.3	13.6	7.6

in a frequency inversion in which BRLA tends to decrease, rather than increase, with frequency from 500 Hz to 1600 Hz.

An important feature of this dramatic decrease in BRLA at 1600 Hz is its relative independence from the details of the layered structure. If special structures were required to achieve the reduction, the variability in naturally occurring layering would restrict the effect to a few special geographic areas. This relative independence from the exact structure suggests that such reductions and associated frequency inversions may actually occur in a wide variety of locations, and that statistical parameters such as mean layer spacing, thickness, number of layers, etc., may be controlling factors.

The exact nature of the layered structure has several important effects. Above 200 Hz it is critically important in predicting the dependence on grazing angle of BRL and especially cw bottom reflection phase shifts. At lower frequencies, where the long wavelength acoustic field averages over the layering, BRL and phase shift nearly equal those computed for an unlayered structure. The details of the layered structure also have an important effect on BRLA at about 800 Hz, but this sensitivity may decrease for larger averaging bands.

Frequency averaging smooths the dependence of BRL on grazing angle. The 1/3 octave averaging used in this study has a considerable effect, and further smoothing may well occur for larger averaging bands such as a full octave. This smoothing effect suggests that caution be used in applying measured band averaged BRL in the analysis of cw propagation.

The physical mechanism responsible for the reduction in near normal incidence BRL is a collective effect of the layered structure. Studies

of BRL using an artificial layered structure made up of identical equally spaced layers show that the constructive interference of reflections from each layer produces the decrease in BRL. Detuning the structure by modifying the layer spacing slightly reduces the magnitude of the decrease in BRL but does not change the frequency interval over which the decrease occurs. Thus, equally spaced, identical layers are not required for the collective resonance effect to be an important mechanism.

IV. ACKNOWLEDGMENTS

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APPENDIX D

OCCURRENCE AND ACOUSTICAL SIGNIFICANCE OF NATURAL GAS HYDRATES IN MARINE SEDIMENTS

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Occurrence and acoustical significance of natural gas hydrates in marine sediments

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This article reviews current knowledge concerning gas hydrates in marine sediments: their chemistry, occurrence, formation conditions, and acoustic properties. In a hydrated sediment the water molecules form an ice-like crystalline structure, which traps the gas molecules within it. This structure can greatly increase compressional sound velocity and may alter shear velocity and absorption processes from those expected for typical marine sediment types. The potential impact of hydrates on underwater acoustics is demonstrated through computations of bottom reflection loss for a hypothetical subbottom structure containing a hydrate zone.

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INTRODUCTION

The effect of the ocean subbottom on underwater sound propagation is an active field of research. Much theoretical and numerical effort is being expended to determine how the geoacoustic profile (depth dependence of acoustically relevant parameters) affects acoustic quantities such as bottom reflection loss, mode attenuation coefficients, group velocities, etc. The results of such work are useful only to the extent that the geoacoustic profiles used actually contain the relevant acoustic parameters of the ocean floor.

This paper discusses one subbottom feature that is seldom included in geoacoustic profiles: hydrate formation in marine sediments. Hydrates are crystalline compounds formed when gas molecules are trapped in an ice-like crystalline structure. Hydrates in marine sediments can significantly alter geoacoustic parameters such as sound speed, shear speed, and absorption, and thus can greatly alter acoustic predictions from those obtained based on nonhydrated sediment structures.

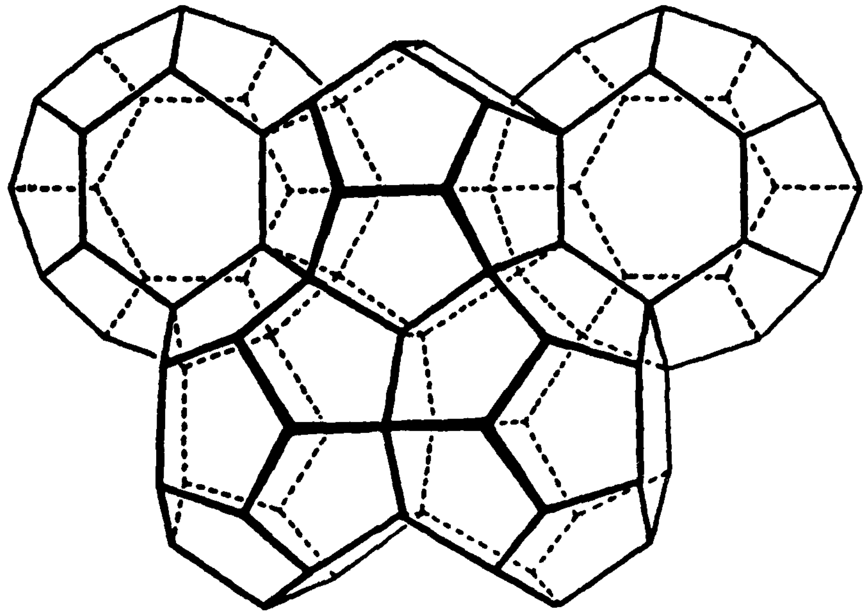
This paper is organized as follows: Section I, the nature of hydrates and their chemistry and occurrence; Section II, the physical characteristics of natural gas hydrates in marine sediments, including conditions for formation, and the results of laboratory and in situ studies of their properties; Section III, evidence for the existence of hydrates in marine sediments; Section IV, some acoustical implications based on a comparison of numerically generated bottom reflection loss from hydrated and nonhydrated sediments; Section V, a summary. The appendix contains a comprehensive bibliography.

I. THE NATURE OF GAS HYDRATES

Clathrate hydrates are a special class of compounds in which an expanded ice lattice forms a cage that contains gas molecules (Fig. 1). These crystalline compounds are formed from a variety of gases, including methane, and can exist at temperatures well above the freezing point of water.

Clathrates (from the Latin word clathratus, which means enclosed by bars of grating), are defined as "the structural combinations of two substances which remain associated not through strong attractive forces but because strong mutual binding of the molecules of one sort makes possible the firm enclosure of the other."[1] Hydrates of natural gas, specifically methane, are members of the class of solids in which gas molecules occupy voids in lattices composed of hydrogen bonded water molecules. These solid solutions of gas molecules in a host lattice exist in a relationship which is nonstoichiometric; the variability of composition depends upon the minimum number of molecules necessary for thermodynamic stability of the lattice and the maximum number of molecules that can fit into the void spaces. Symmetry of the interactions between the gas molecules and the water molecules that form the cages requires preferred orientations of the void cages which become increasingly occupied at low temperatures; however, a large degree of rotational freedom of gas molecules is observed, resulting in hydrates that are stable for a wide range of temperatures.[1]

Three conditions are necessary for the formation of natural gas (methane) hydrates: sufficiently high pressure, sufficiently low



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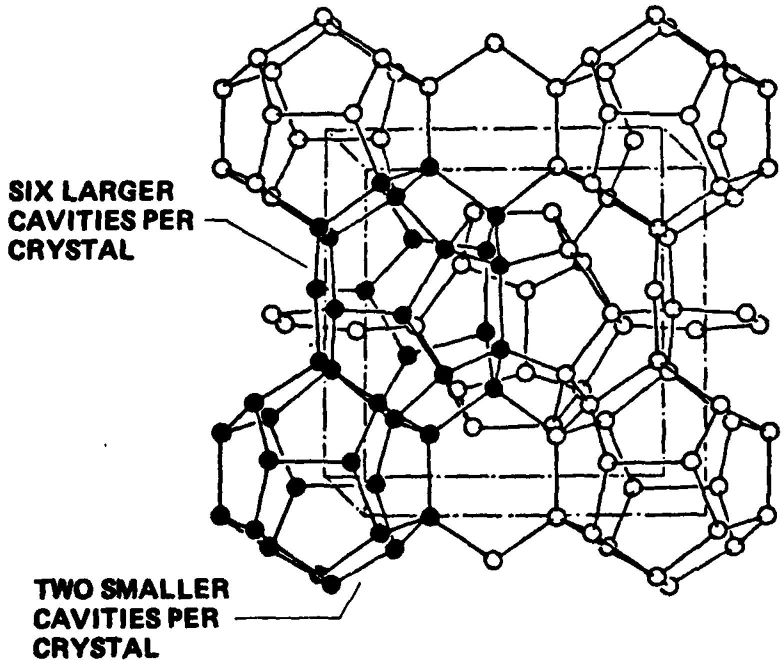

(b)

FIG. 1. Structures of hydrate lattice (a) the 12 Å hydrate lattice. The pentagonal dodecahedron (from Ref. 2) is formed by 20 water molecules. The tetrakaidecahedra formed by 24 water molecules have 2 opposite hexagonal faces and 12 pentagonal faces. (b) structure I hydrate lattice (from Ref. 17).

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Fig. 1
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temperature, and an adequate concentration of methane. Figure 2 shows the temperature-pressure conditions suitable for hydrate formation, assuming a saturation level of methane. The presence of salt in the water (seawater is approximately 3.5% salt) will shift the curve slightly to the left. The addition of higher molecular weight gases, such as ethane and propane, to the mixture will have dramatic effects on the formation conditions for hydrates. For example, 1% propane in the gas mixture can reduce the pressure at which the hydrate forms by nearly 40%.[2]

The formation conditions for methane hydrate are encountered in several regions throughout the solar system.[3] Spectral studies and temperature-pressure calculations indicate that methane hydrates are probably a constituent of the atmospheres of the outer planets Uranus and Neptune. Methane hydrates possibly occur in the rings of Saturn, and calculations indicate that significant quantities may occur on the satellites of Jupiter and Saturn. Several models proposed for comets suggest that gas hydrates are a major constituent and it is also possible that hydrates are present in particles of interstellar dust.

Calculations based on laboratory studies of hydrates show that many areas on the earth are suitable for hydrate formation.[4] The Soviet Union has discovered large zones of gas hydrates in the Messoyakhskoye gas field beneath the Siberian permafrost, and similar zones have been detected in Canada and Alaska. The Soviets are currently producing these frozen gas fields, and they are convinced that hydrates will add huge amounts of gas to their fuel reserves.[5] In the permafrost areas,

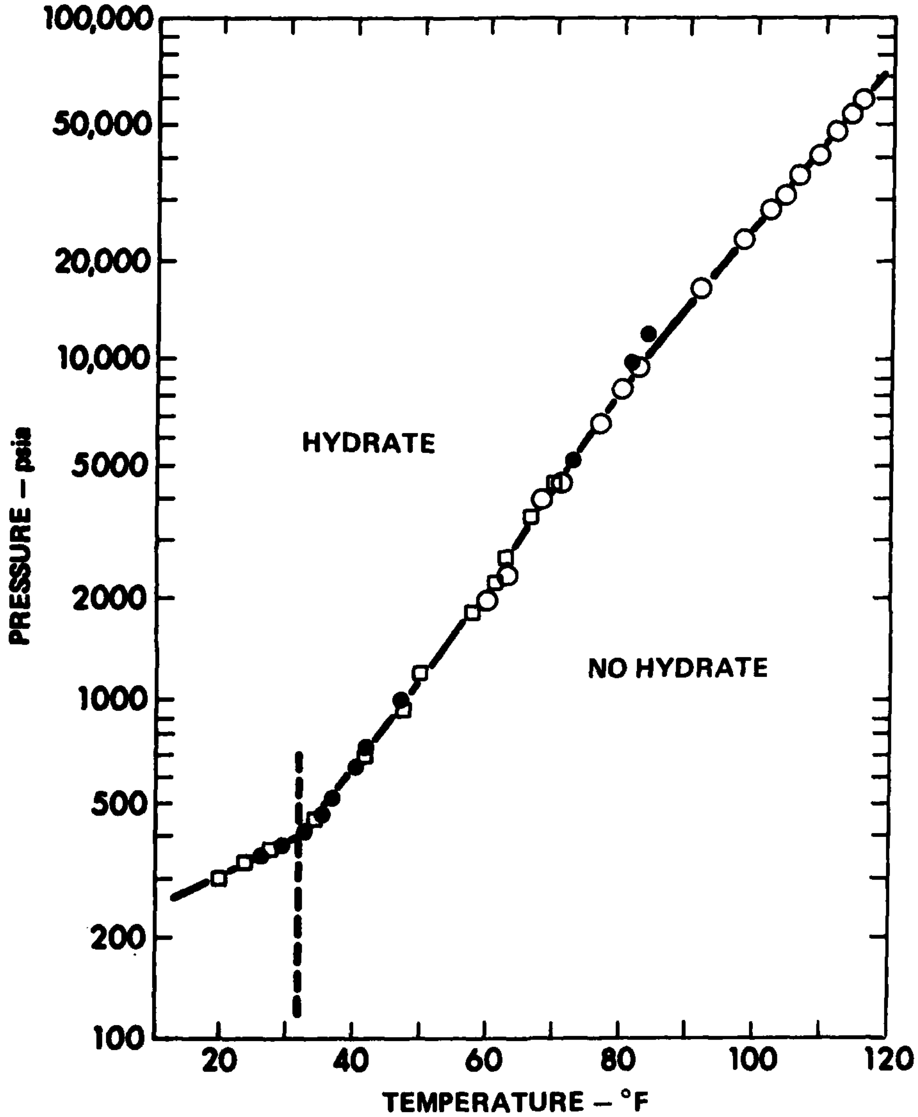

FIG. 2. Hydrate formation conditions for methane (from Ref. 17).

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Fig. 2
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zones of abnormally low geothermal gradients increase the depth to which hydrates may be found. Gas hydrate deposits are accompanied by a reduction in source rock pressure. As a result, concentrations of the methane in the deposits are greatly increased. Thus the Soviet expectations that frozen gas will constitute a significant energy resource appear to be well founded.

II. PHYSICAL PROPERTIES OF NATURAL GAS HYDRATES IN MARINE SEDIMENTS

Temperature and pressure conditions suitable for hydrate formation are found in the deep ocean environment. At depths exceeding about 400 m, hydrates may exist from the sediment surface to a considerable depth in the sediment. The depth to which hydrates may occur in the sediment is governed by the local geothermal gradient. This depth has been calculated to be approximately 500-1000 m, based on average geothermal gradients, but may vary considerably from these average values.[6,7] Figure 3 shows depths at which hydrates may occur in sediment for given water depth and bottom water temperature, where an average geothermal gradient is assumed. Soviet scientists believe that enormous quantities of methane exist in the sediments of seas and oceans.[5]

The requirement of saturation level methane (in sediments, this would be pore water methane) could be fulfilled from two sources: biologically generated methane, and methane which migrates and diffuses from the deeper levels of the sedimentary mantle of the earth's crust. Mantle generated methane, which diffuses upward through marine sediments, would necessarily pass through the solid phase, since diffusion rates would be far less than the rates of saturation at great

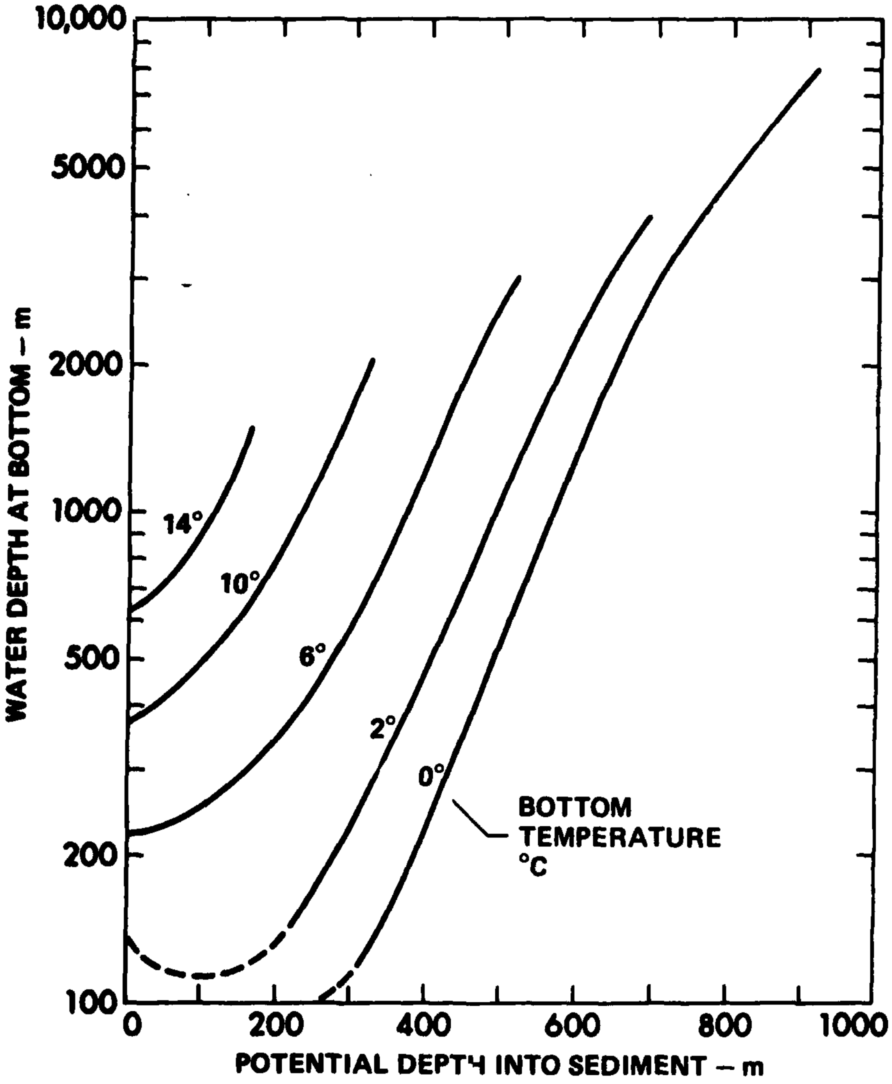

FIG. 3. Potential depth of hydrate formation in sediments from natural gas (the hydrate is stable under conditions described by depth of water and sediment to the left of each line) (from Ref. 18).

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Fig. 3
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depths in the sediment. Near-surface zones of hydrates would form only if the rate of generation of methane exceeded the rate of diffusion from the sediment into the seawater. The precise mechanism of biologic methane generation in ocean sediments is not known, but several mechanisms have been proposed, and it is possible that these mechanisms may be operating simultaneously or alternately.[8] The various degradation products of fats, carbohydrates, and proteins may be metabolized in a variety of ways, leading to the production of hydrocarbons. It has been suggested that bacteria may directly produce methane from fatty acids, or they may complement a group of reactions that result in hydrocarbon production.[8] As a result of the complexity of the methane generation system and the additional complexity of sedimentary structures in ocean sediments, the structure of hydrate zones may vary widely. It is reasonable to assume that hydrates exist in diffuse patches as well as continuous zones within the sediments.

Laboratory and in situ studies indicate that hydrates interact with marine sediments to effect marked geoacoustic changes. Experiments have shown that acoustic compressional velocities increase when hydrates are present in the artificial sediments; and because of the limited conditions of these experiments, it is believed that velocity increases in actual marine sediments may differ from those observed in the laboratory. The nature of the interaction of hydrates with sediments suggests that shear wave velocity increases would also be affected. In addition to velocity increases, increases in resistivity and decreases

in thermal conductivity have been observed, and shear wave and compressional wave attenuation changes are likely to be observed as well.

A series of experiments by Stoll[9] was performed in which compressional wave velocities were measured in sediment containing artificially formed gas hydrate. Methane was introduced into an isothermal (+3.3°C), high pressure (1100 psi) chamber containing an artificial sediment with seawater, and wave velocities were continuously measured throughout the cycling. In one case, the compressional velocity was found to increase from 1.85 km/sec to 2.67 km/sec. Although temperature and pressure conditions were kept within a narrow range, in each case significant wave velocity increases were observed (Fig. 4).

These experiments also demonstrate that hydrates interact with sediments to produce a firm mass of particles bonded by the hydrate crystals. Although the mechanism has not been explained, hydrates increase the rigidity by filling the sediment pore space and locking the grains together. The degree to which sediments containing hydrates experience velocity increases depends upon the quantity of hydrate occupying the interstices between grains; the sediments used in experiments were saturated with gas over a relatively short period of time and were contained under limited pressure/temperature conditions. It is possible that in some cases naturally occurring hydrates in sediments occupy pore space more completely, thus effecting even greater shear and compressional velocity increases. On recent legs (67,76) of the Deep Sea Drilling Project, gas was encountered in increasing

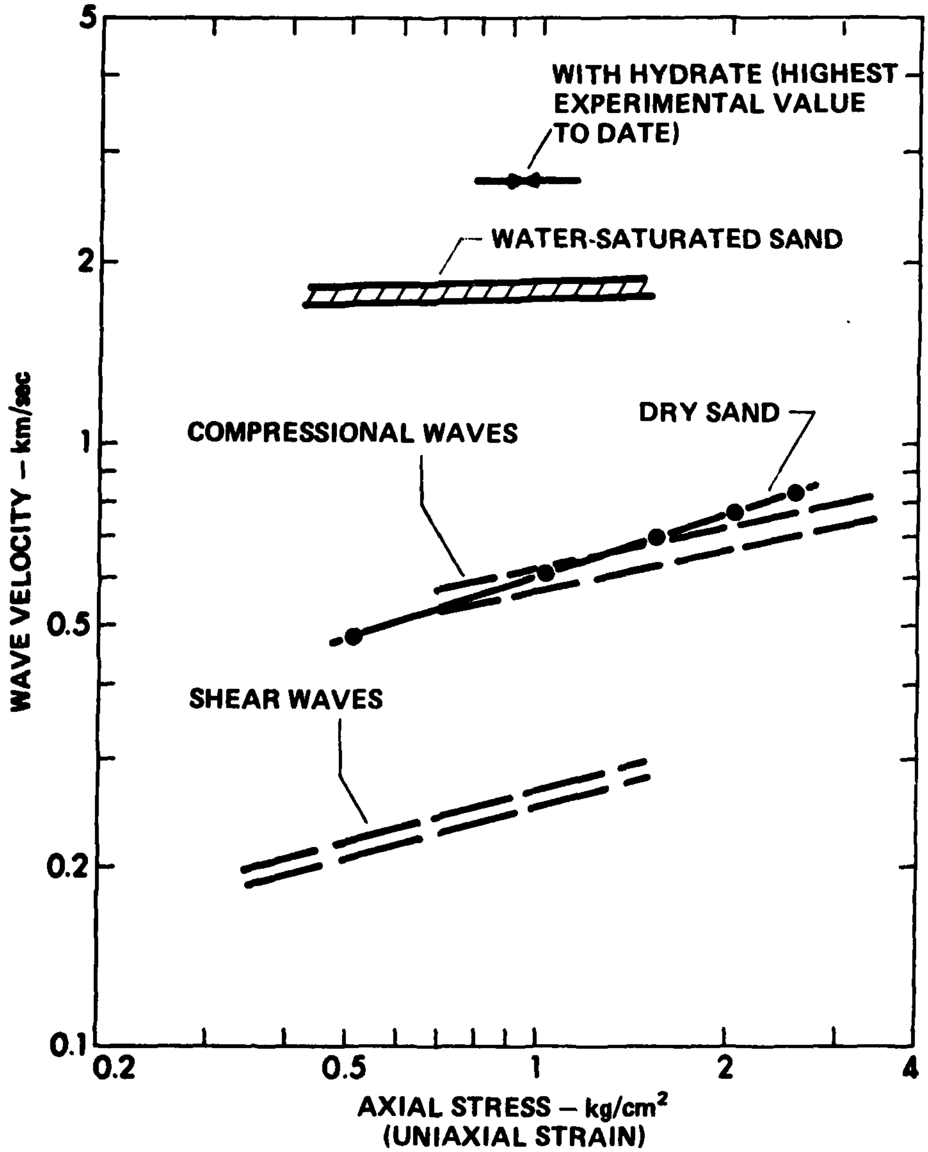

FIG. 4. Wave velocity in sediment for various conditions (from Ref. 18).

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quantities with depth of drilling, and seismic velocity studies in this area revealed anomalously high velocity values;[10] both suggest the presence of gas hydrates.

In addition to the laboratory velocity experiments, several measurements of thermal conductivity of sediments containing hydrates have been performed. Contrary to the results one would expect for frozen sediments, thermal conductivities decrease in sediments containing hydrates. In experiments described by Stoll,[9] thermal gradients in sediments containing hydrates are somewhat higher than expected in the given sediment type. Well logs have shown that sediments containing gas hydrates have high resistivities as well as high velocities, a further indication of the significant physical interaction of hydrates with sediments.

III. EVIDENCE OF HYDRATES IN MARINE SEDIMENTS

Perhaps the most dramatic effect that has been observed in connection with hydrates in marine sediments is the so-called "bottom simulating reflector" (Fig. 5). Bottom simulating reflectors were first discovered in the Blake Bahama Outer Ridge off the southeastern coast of the United States.[10] Several reflectors have been observed[11] in the Western North Atlantic, the Arctic Ocean, the North Pacific Ocean, and the Bering Sea. Bottom simulating reflectors have also been described in the Gulf of Mexico, the Caribbean Sea (off the coast of Colombia and Panama), and off the Pacific coasts of Mexico and Central America.[11]

A bottom simulating reflector is a subbottom seismic feature that parallels the ocean floor topography. These reflectors have been

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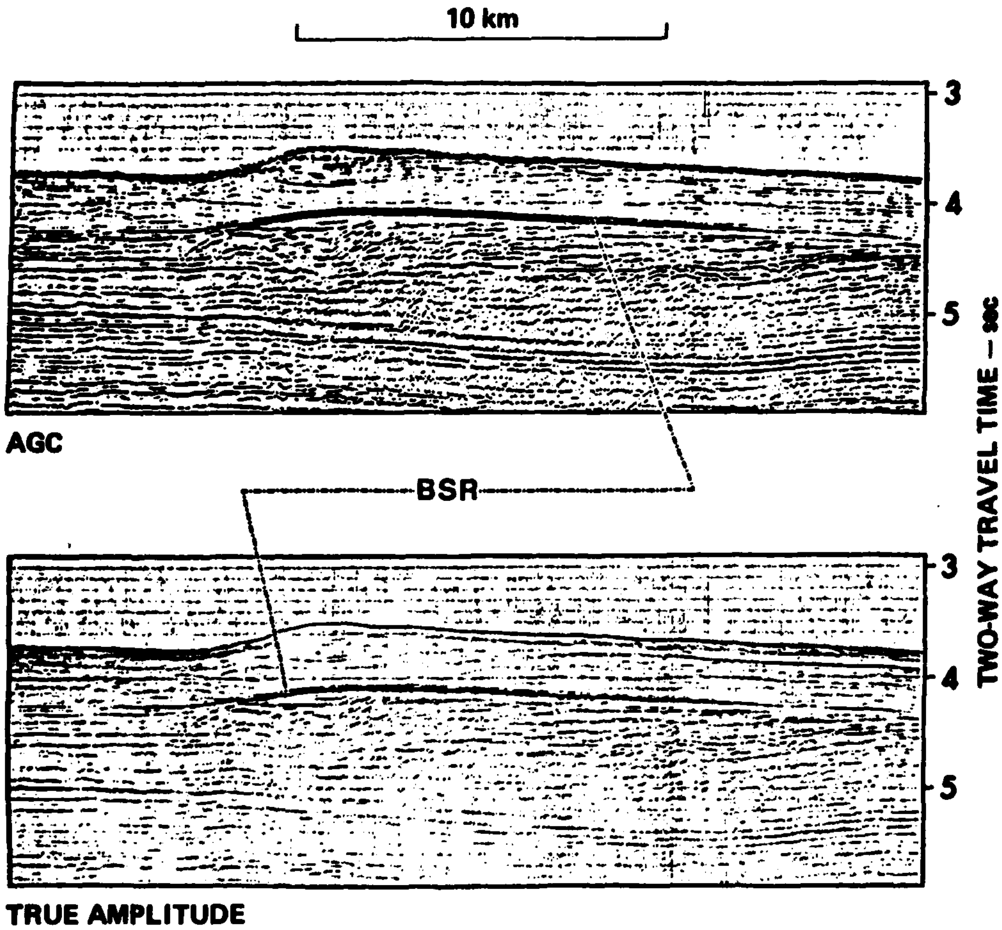

FIG. 5. Bottom simulating reflector (from Ref. 13).

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observed at depths between 200 and 1000 m below the sediment-water interface, and occur in regions where the water depth is greater than 400 m. The bottom simulating reflectors transect local bedding in many instances, clearly indicating that these features are not lithologic in nature. Subbottom depth ranges of hydrate stability have been calculated based on laboratory conditions of hydrate stability, and these predictions conform closely to the observed depths of the bottom simulating reflector. Increasing pressure from the depth of water overlying the sediment accounts for the increase in subbottom depth expected for a hydrate zone; observations confirm that, in areas where reflectors continue under sediment in increasingly deeper water, the reflectors occur at a greater depth in the sediment. On the basis of laboratory calculations[9] and seismic observations,[10,11,12,13] it is concluded that these reflectors are the result of the phase change between hydrate and free gas. The phase change is a result of the increase in temperature with sediment depth, and the reflection is effected by a strong mismatch between the upper high velocity hydrate zone and the lower low velocity free gas zone.

Acoustic velocity measurements have been undertaken in areas where bottom simulating reflectors have been detected, and anomalously high velocity values have been observed. In addition, reflections that are related to gas hydrate zones are characterized by a reflection polarity reversal and a large reflection coefficient.[13] This is the result of a high to low velocity change. It has been postulated that large quantities of free gas are trapped beneath the relatively impermeable

gas hydrate layer. The concentration of gas would cause a density and velocity decrease, which would result in a negative reflection coefficient. Observations[10] of bottom simulating reflectors in the Blake Outer Ridge, the Western Caribbean, and the Eastern Pacific (Panama area) show the large polarity reversals expected. It has also been shown that there is a marked decrease in reflection amplitude of the bedding above the anomalous bottom simulating reflector. This observation is consistent with the existence of a gas hydrate zone, since such a zone would contribute to the homogeneity of a bedded sediment.

An area of controversy concerning the bottom simulating reflector is the thickness of the actual hydrate layer above the reflecting horizon. It is possible that the hydrate layer occurs relatively close to the lower part of the zone of hydrate stability, although the layer can theoretically continue up to the surface. Since reflections above the bottom simulating reflectors have been limited to those caused by local bedding, it is likely that concentrations of hydrate near the surface are too small to effect an appreciable change in acoustic velocity. However, in the case of the bottom simulating reflector, it is assumed that the source of methane is below the zone of hydrate stability. Shipley[10] has pointed out that methane migrating upward through the sediment would be retarded by a hydrate barrier. Ultimately, though, the thickness of a hydrate zone would depend not only on the location of the source of methane production, but on the

rate at which the methane was produced as well as the rate at which methane was diffused within the particular type of sediment in question.

A number of localized accumulations of gas, which are observed as bright spots on continuous seismic refraction profiles, have been observed in the Gulf of Oman[12] and other areas[11,12,13,14] (Fig. 6). The anomalously high amplitude reflections represent a horizon similar to the bottom simulating reflectors but without the considerable lateral extent. These bright spots occur at a depth expected for the hydrate-to-free-gas phase change, and probably represent hydrate layers trapping free gas under water. As in the case of the bottom simulating reflector, these bright spots transect local bedding and exhibit phase reversals and travel time changes beneath the bright spots; however, the bright spots are not confined to particular lithologic structures associated with the bottom simulating reflector. Observed[15,16] reflectivities of 0.2-0.3 are much higher than would be expected from a stratigraphic horizon, and calculations[12] based on local geothermal gradients closely conform to the hydrate layer theory.[12] The curvature of these bright spots parallel the ocean floor topography rather than the local bedding, further indicating the presence of a hydrate zone, which is more sensitive to the depth-dependence temperature than to lithologic changes.[17,18]

IV. ACOUSTICAL SIGNIFICANCE OF NATURAL GAS HYDRATES IN MARINE SEDIMENTS

To determine the acoustical significance of natural gas hydrates in marine sediments, their effect on the plane wave reflection coefficient of the ocean bottom, R, was investigated using a computation model.

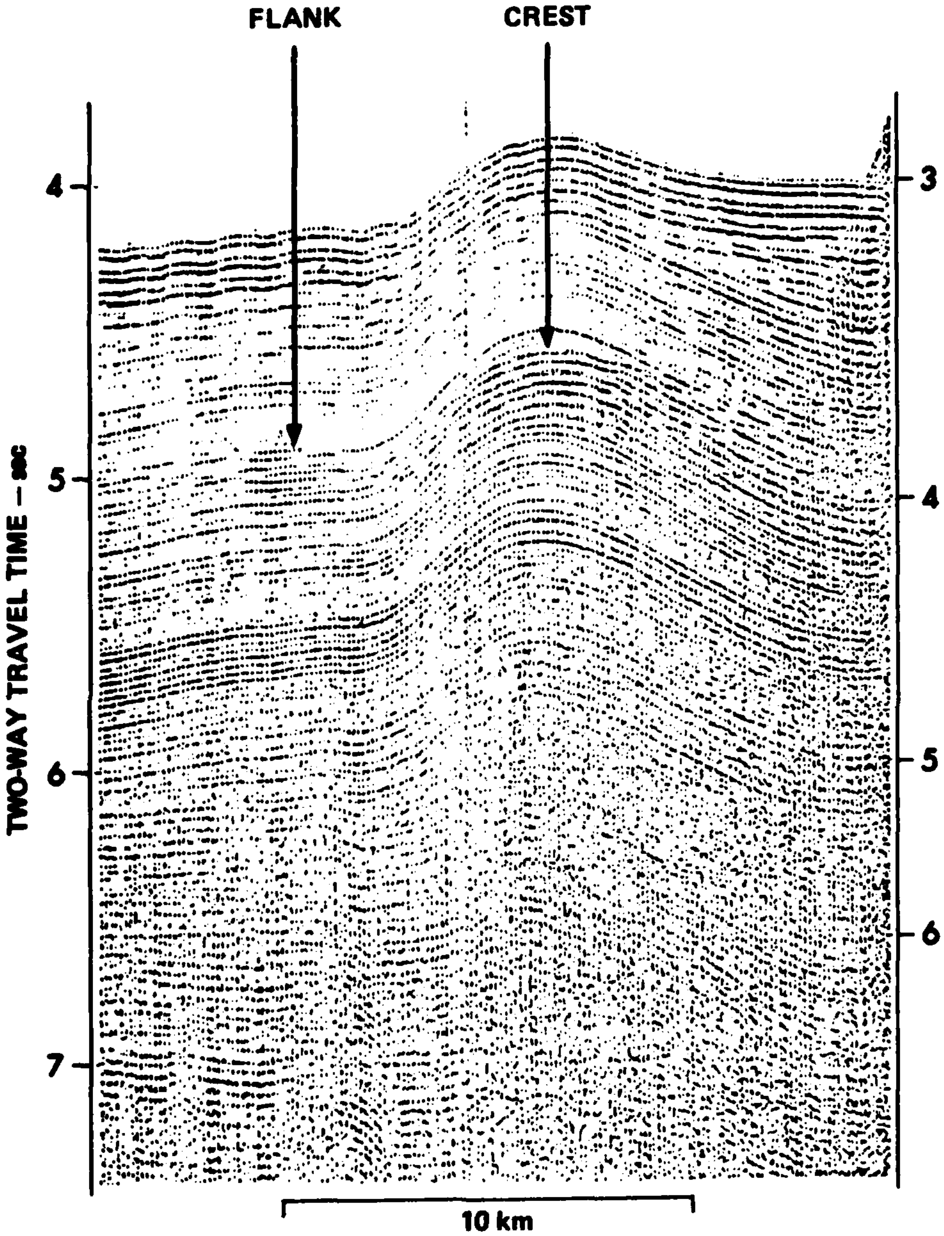

FIG. 6. Seismic bright spot in the Gulf of Oman (from Ref. 12).

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Bottom reflection loss, BRL = $-20 \log_{10}(R)$, for two hypothetical hydrate geoacoustic profiles was compared to that for an unhydrated profile at two frequencies, 50 and 1600 Hz.

The computational model used is an extension of the single solid layer model (described in detail in Ref. 15) to the case of an arbitrary combination of fluid and solid layers. The basic assumptions embodied in this model are: (1) coupling between shear and compressional waves occurs only at interfaces between layers, and (2) Helmholtz equations with depth dependent wavenumber describe the propagation of shear and compressional waves.

Table I contains the unhydrated geoacoustic profile. The parameters are typical of deep ocean marine sediments.[16]

Tables II and III contain the hydrated versions of the profile in Table I. The hydrate zone begins 10 m below the water-sediment interface, not at the water-sediment interface, and extends 100 m. Biological activity and bottom currents are expected to mix the upper part of the sediment, increasing gas transport and reducing the likelihood that the saturation level of gas needed for hydrate formation is present. The lower edge of the hydrate zone generally occurs at that depth where the temperature has increased to the point that hydrate formation is no longer possible. The value of 100 m was chosen as being in rough agreement with theoretical estimates and geophysical measurements of the depth to the bottom of a hydrate zone.[17] In both tables, the hydrate zones have an increased compressional velocity consistent with those expected from laboratory and in situ

TABLE I

Geoacoustic profile for a typical unhydrated deep ocean sediment: c_p is the compressional velocity, c_s is the shear velocity, ρ is the density, k_p is the compressional attenuation, k_s is the shear attenuation. Constant gradients are assumed between depths at which parameters are specified. Water column and substrate are homogeneous half spaces.

Depth (m)	c_p (m/sec)	k_p (dB/m-kHz)	ρ (g/cc)	c_s (m/sec)	k_s (dB/m-kHz)
Water	1530	...	1.043	...	...
0	1515	0.026	1.59	127	15.0
10	1533	0.024	1.60	142	13.9
100	1638	0.012	1.67	377	6.9
200	1750	0.015	1..80	442	8.7
300	1851	0.020	1.91	499	11.5
400	1943	0.020	2.02	558	11.5
500	2026	0.015	2.10	619	8.7
Substrate	4600	0.020	2.50	2270	0.070

TABLE II

Geoacoustic profile for a soft hydrate in a typical deep ocean sediment: c_p is the compressional velocity, c_s is the shear velocity, ρ is the density, k_p is the compressional attenuation, k_s is the shear attenuation. Constant gradients are assumed between depths at which parameters are specified. Water column and substrate are homogeneous half spaces.

Depth (m)	c_p (m/sec)	k_p (dB/m-kHz)	ρ (g/cc)	c_s (m/sec)	k_s (db/m-kHz)
Water	1530	...	1.043	...	...
0	1515	0.026	1.59	127	15.0
10	1533	0.024	1.60	142	13.9
10	2700	0.024	1.60	142	13.9
100	2700	0.012	1.67	377	13.9
100	1638	0.012	1.67	377	6.9
200	1750	0.015	1.80	442	8.7
300	1851	0.020	1.91	499	11.5
400	1943	0.020	2.02	558	11.5
500	2026	0.015	2.10	619	8.7
Substrate	4600	0.020	2.50	2270	0.070

TABLE III

Geoacoustic profile for a hard hydrate zone in a typical deep ocean sediment: c_p is the compressional velocity, c_s is the shear velocity, ρ is the density, k_p is the compressional attenuation, k_s is the shear attenuation. Constant gradients are assumed between depths at which parameters are specified. Water column and substrate are homogeneous half spaces.

Depth (m)	c_p (m/sec)	k_p (dB/m-kHz)	ρ (g/cc)	c_s (m/sec)	k_s (dB/m-kHz)
Water	1530	...	1.043	...	...
0	1515	0.026	1.59	127	15.0
10	1533	0.024	1.60	142	13.9
10	2700	0.024	1.60	1564	0.024
100	2700	0.012	1.67	1564	0.012
100	1638	0.012	1.67	377	6.9
200	1750	0.015	1.80	442	8.7
300	1851	0.020	1.91	499	11.5
400	1943	0.020	2.02	558	11.5
500	2026	0.015	2.10	619	8.7
Substrate	4600	0.020	2.50	2270	0.070

measurements. Density changes due to hydration were assumed to be negligible.[9,13]

The least known geoacoustic parameters of hydrated marine sediments are the shear wave velocity and the attenuations of both shear and compressional waves. In the absence of measured values, these parameters were assigned as follows. The processes leading to compressional wave absorption were assumed to be only slightly modified by the replacement of the pore water by the crystalline hydrate structure. To reflect this assumption, the compressional wave attenuation for the hydrated sediment was set equal to that for the unhydrated sediment.

The two geoacoustic profiles for the hydrate zones in Tables II and III differ in their shear wave parameters. The shear wave velocities were assigned using the relationship between the compressional velocity c_p, shear velocity c_s, density, and the Lamé parameters.

$$c_p^2 = (\lambda + 2\mu)/\rho$$

$$c_s^2 = \mu/\rho \quad .$$

An estimate of the minimum possible shear speed was obtained by assuming that the increase in c_p upon hydration occurs entirely through an increase in λ with μ remaining constant. This leaves c_s unchanged by hydration and leads to the "soft" hydrate profile in Table II. Since μ is unchanged in this case the shear wave attenuation was also set equal to that of the unhydrated sediment. Holding λ constant and allowing μ to increase yields an estimate of the largest value c_s can have, resulting in the greatly increased c_s found in the "hard" hydrate

geoacoustic profile of Table III. In this case the increase in c_s is so large that the hydrate crystal structure is now supporting the bulk of the shear motion rather than the structure made up of the sedimentary particles. This leads to the conclusion that the loss processes in the hydrate crystals now dominate the shear wave absorption. These processes should be at least approximately related to the compressional loss processes, which could be quite low. Hence the shear wave attenuation for this case is decreased considerably from the value typical of an unhydrated sediment to that of the compressional wave attenuation. The two hydrate zones in Tables II and III then represent the two extremes of possible shear wave parameters.

Figure 7 compares the computed BRL at 50 Hz for the three geoacoustic profiles. BRL was evaluated at 1° intervals between 0-90°. The no-hydrate case serves as a reference for evaluating the effect of the hydrate zone on BRL, which is easily interpreted for this case. Below about 41°, compressional wave absorption within the sediment accounts for the nonzero value of BRL. The oscillatory structure is the result of interference between energy refracted within the sediment and that directly reflected at the water-sediment interface. Beyond 41° the compressional wave interacts with the substrate interface and additional losses due to sediment shear wave excitation are important.[19] The greatly increased loss between about 47-70° is due to coupling to shear waves in the substrate; the critical angle for substrate shear waves is about 47.5°. Beyond about 70° substrate compressional waves can also propagate.

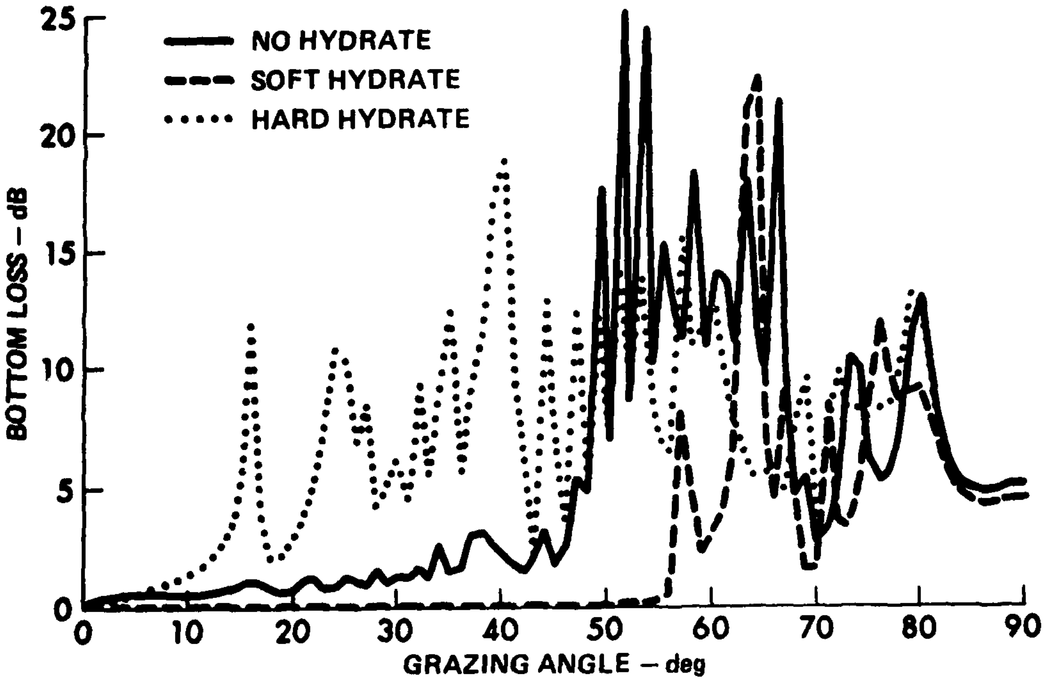

FIG. 7. Bottom loss versus grazing angle for hard, soft, and unhydrated sediments at 50 Hz.

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Fig. 7
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The soft hydrate curve in Fig. 7 has almost no loss until about 56°. This is the critical angle for compressional wave penetration into the hydrate zone. Below 56° compressional wave absorption within the top 10 m produces little loss and almost all the sediment penetrating energy is reflected from the top of the hydrate zone. Coupling to shear waves at the top of the hydrate zone is negligible, as is expected from the relatively low shear speed.[20] Beyond 56° BRL has the same behavior qualitatively as in the unhydrated case, and partial reflection from the bottom of the hydrate zone is probably the cause of the reduced loss to sediment shear waves.

The hard hydrate BRL in Fig. 7 substantially differs from the soft hydrate and no-hydrate results, particularly at low angles where BRL is greatly enhanced. The large value of c_s allows efficient coupling to shear waves in the hydrate zone and also enhances the coupling to the heavily attenuated shear waves in the unhydrated sediment surrounding the hydrate zone.

Figure 8 shows BRL at 1600 Hz for the three geoacoustic profiles. The computations were done every 3° between 0-90°. This sampling obscures some of the detail in the curves, particularly for the hard hydrate case, but was necessary because of the large computational effort required to solve the wave equations by numerical integration at 1600 Hz.

The no-hydrate curve in Fig. 8 increases to a peak near 15° and then decreases to a nearly constant value of about 14 dB beyond about 30°. The nearly constant value beyond 30° is roughly that produced

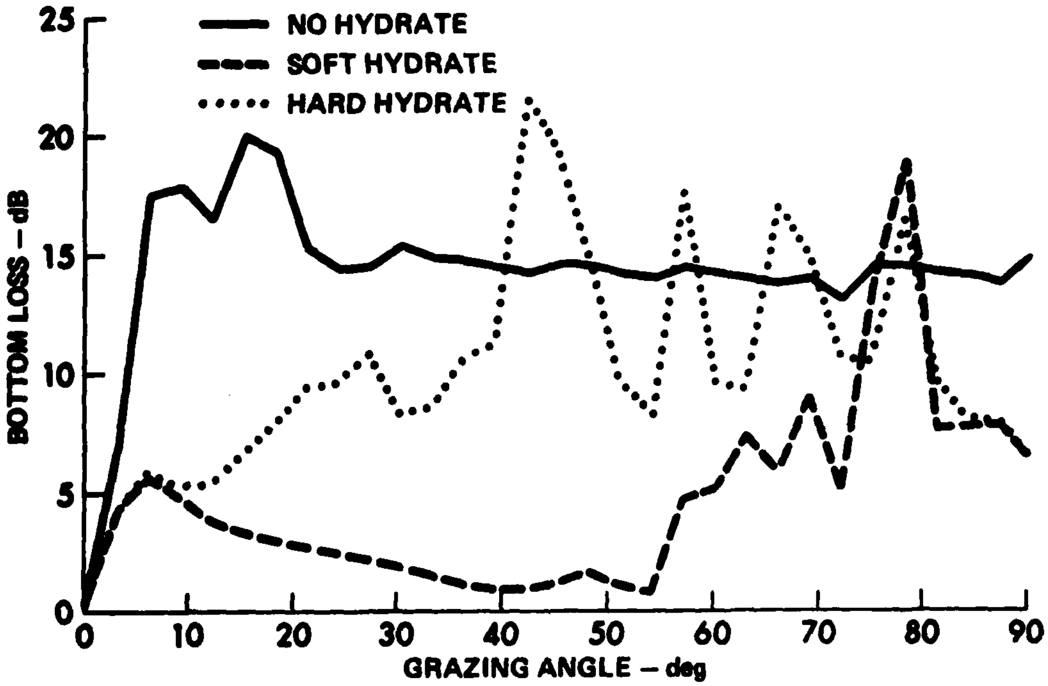

FIG. 8. Bottom loss versus grazing angle for hard, soft, and unhydrated sediments at 1600 Hz.

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Fig. 8
Daniels

under the assumptions that all sediment penetrating energy is absorbed and that shear wave generation at the water-sediment interface is negligible; i.e., the fluid-fluid reflection coefficient accurately models the reflection process. BRL at near-normal incidence (90° grazing angle) from this reflection coefficient is about 14 dB, in agreement with the computation. The assumptions behind this interpretation are met since generation of sediment shear waves at the water-sediment interface is not an important process for deep ocean sediments,[20] and the increase in attenuation with frequency[16] leads to the absorption of sediment penetrating energy, particularly at large angles.

The soft hydrate produces a significantly lower BRL at 1600 Hz. Figure 8 shows that BRL from the soft hydrate is roughly 2 dB between $15\text{-}55^{\circ}$ compared to about 14 dB obtained for the reference, no-hydrate case. This reduction is the result of reflection of the compressional wave from the large impedance contrast at the top of the hydrate zone. Beyond 55° the compressional wave penetrates into the hydrate zones and BRL increases as this energy is absorbed within the hydrate zone. Reflection from the bottom of the zone probably produces the structure in BRL between $60\text{-}90^{\circ}$.

At 1600 Hz the hard hydrate zone has a BRL roughly between the no-hydrate and the soft hydrate zone results. Figure 8 shows that the hard hydrate BRL oscillates about a value of about 11 dB. The increase in level above the soft hydrate is due to coupling to shear waves in the hydrate zone and their absorption. The oscillations are probably due to interference from energy reflected from the bottom of the zone.

Two conclusions can be drawn from these computations of BRL. First, the results obtained from reasonable estimates of the maximum and minimum shear parameters of hydrated marine sediments differ so greatly at both low (50 Hz) and high (1600 Hz) frequencies that accurate predictions of bottom reflection loss cannot be made. Research is needed to determine the actual shear wave parameters. Second, even with this uncertainty in shear wave parameters, it is clear that the existence of natural gas hydrates in marine sediments can significantly alter bottom reflection loss from that expected from unhydrated sediments. By implication, other quantities of interest in underwater acoustics related to bottom loss, such as propagation loss, can also be significantly affected.

V. SUMMARY

The interaction of underwater sound with the ocean subbottom sediments is an active field of research; thus, the structure of marine sediments from chemical, geologic, and geophysical viewpoints are of prime importance. The crystal-like gas hydrate molecules that are found in marine sediments can significantly alter the geoacoustic properties of these sediments.

Laboratory evidence indicates that significant increases in compressional sound velocity (i.e., from 1.8 to 2.7 km/sec) occur as well as changes in the thermal and electrical properties. In situ results confirm the effects observed in laboratory experiments. Whether similar changes occur in shear velocities, compressional and shear

attenuations, and scattering in sediments containing hydrates is a question that remains to be answered.

Evidence of widespread occurrence of hydrates has been presented in this paper. The temperature and pressure conditions necessary for the formation of hydrates are found globally. Considerable research is needed to determine the actual extent of gas hydrates as well as the possible structures hydrates can assume. Bottom simulating reflectors and seismic bright spots are believed to be caused by hydrate zones; dramatic acoustic changes would also be caused by both continuous hydrates zones and diffuse patches of hydrates, which are not detectable under normal seismic profiling conditions.

Preliminary results indicating the acoustical effects of subbottom hydrate zones were presented in this paper. Through calculations of bottom reflection loss, these results show that hydrates have a potentially profound impact on underwater acoustics.

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